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13. ABSTRACT (Maximum 200 words)

This Phase I study demonstrated the basic feasibility of developing a hybrid active/passive noise canceling stethoscope for rotorcraft aeromedical evacuation use. The hybrid design makes full use of active and passive noise reduction techniques, and incorporates: 1) primary and reference stethoscopes to pickup the relevant patient sounds and to measure the surrounding ambient noise environment; 2) a hybrid noise canceling headset used by the medic to listen to the transduced heart/lung sounds and to reduce the ambient noise levels; and 3) a custom ANC processor to further reduce noise pickup at the primary stethoscope. Under the Phase I effort we reviewed commercially-available hardware, assembled candidate components in a prototype system, developed custom ANC algorithms for patient signal processing, and demonstrated end-to-end operation of the system. Engineering evaluations of noise reduction capability and psychoacoustic evaluations of patient sound clarity were made to demonstrate system feasibility and to identify system requirements for full-scope prototype development under a follow-on program. The Phase I evaluation clearly demonstrated the system's ability to extract clean patient sounds in high ambient level noise, in situations in which one would normally experience inaudible patient sounds using conventional or electronic stethoscopes.

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Active Noise Cancellation Stethoscope

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1. INTRODUCTION

Auscultation of heart and lung sounds during aeromedical evacuation can be seriously compromised by the high ambient noise levels associated with normal rotorcraft operation. Several sources of noise exist: engine, transmission, main/tail rotors, and wind noise. Their interaction within the fuselage is complex, dependent on patient location, and time-varying due to the variety of maneuvers and flight conditions encountered during a normal mission. Furthermore, the compound noise spectrum, although characterized by harmonics associated with the different mechanical rotating components, is fairly broadband, reaching from very low sub-auditory vibrational frequencies (10 Hz) to midrange acoustic frequencies (10 kHz). The low frequencies in particular (< 1 kHz) cause significant problems during auscultation, since heart/lung sounds are characterized by acoustic signatures in the same bandwidth.

These characteristics severely limit the applicability of a number of noise reduction techniques. Simple passive acoustic isolation is not sufficient by itself because low-frequency noise components will still likely mask the patient sounds of interest. Electrical transduction of the signal, followed by noise-matched active filters, would provide an improvement (especially over a simple straight electrical transduction/amplification of the signal), but the time-varying nature of the noise will lead to considerable filter pass-through, because of the fixed filter design. On-line noise spectrum modeling driving an adaptive filter could be used to ameliorate this problem, but the complexity of the ambient sound spectrum argues against the feasibility of developing an accurate and efficient spectral noise model.

We believe that the most effective solution involves a hybrid approach utilizing both passive acoustic isolation and active noise cancellation (ANC) technologies. By using a separate measurement of the acoustic noise environment surrounding the medic and patient, an ANC device can track the complex and time varying changes in the noise, and compensate for them in real-time. This provides the medic with a significantly enhanced signal-to-noise (S/N) ratio, which, in turn, improves his/her ability to hear critical sounds and make the correct physical assessment of the patient. This approach is in direct contrast with a non-ausculatory monitoring approach, which relies on machine pattern recognition of high noise heart/lung sounds. We believe that the ANC stethoscope approach we are proposing holds significant advantage over a non-ausculatory approach because of the richness of potential heart/lung sounds and the extensive diagnostic skills of the (human) medic.

A schematic diagram of the monitoring environment is given in figure 1.1. Here we show the medic monitoring the patient with a conventional stethoscope. We also show a generic sound source, representing the complex noise environment generated by the several sources noted earlier. For simplicity, we model these noises as impinging on the medic/stethoscope/patient "system" at three separate points. Noise signal N_1 acts directly on the medic's auditory system, bypassing the stethoscope. This is a direct **ambient path**. Noise signal N_2^S acts on the stethoscope itself, at any point from the contact point with the patient, to the medic's ear pieces. The impinging noise spectrum for N_2^S entering through this **stethoscope path** will naturally be modified by the acoustic transfer function of the stethoscope through this path. Finally, noise signal N_2^P acts on the patient, its spectrum shaped by the acoustic transmission characteristics of the trunk, and picked up by the stethoscope. This **patient path** sums directly with the stethoscope path, at the stethoscope bell. In all of this, the medic is attempting to pick up the heart/lung sounds (signals) generated by the patient.

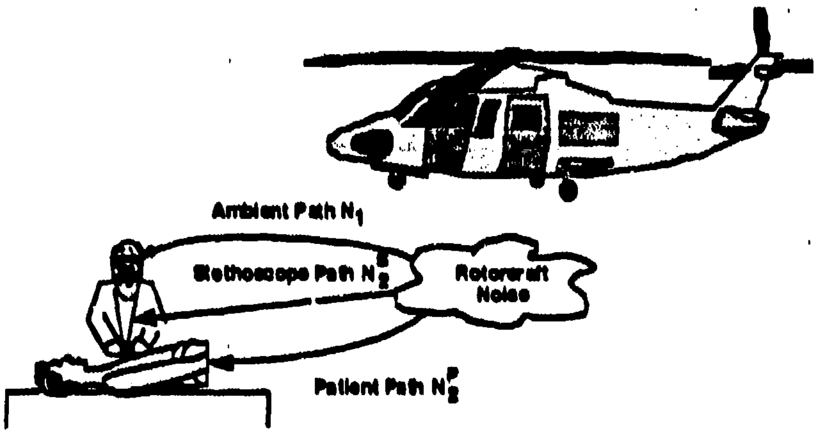


Figure 1.1: Noise Environment for Auscultation in Aeromedical Evacuation

While it is theoretically possible to design an ANC stethoscope to cancel out all three noise sources at once, this approach could lead to a fairly complex implementation, because of the very different spectra characterizing the ambient (N_1), stethoscope (N_2^S), and patient (N_2^P) noises. We can reduce this complexity by proposing a specific ANC compensator for each source, but this imposes excessive hardware costs in the final configuration. A compromise solution is to deal directly with the ambient noise (N_1), and separately with the combined stethoscope-patient (N_2^S - N_2^P) noises. Specifically, we propose the use of a commercially available ANC headset or helmet to deal with the N_1 noise, and the development of an electronic ANC stethoscope to deal with the N_2^S - N_2^P noise. In combination, they should provide full coverage across the medic/stethoscope/patient "system," and allow for tuning of the individual components as required by the characteristics of the three noise sources.

1.1 Technical Objectives

The primary objective of this Phase I study was to design and evaluate the feasibility of a hybrid active/passive noise cancellation stethoscope for rotorcraft aeromedical evacuation use. The effort defined the scope of the problem, identified the requirements to be met by the proposed system, and designed, developed, and evaluated a prototype design. Basic questions addressed during the effort were:

- What are the critical breath sounds to be picked up during auscultation, what is the extent of the rotorcraft noise environment, and what is the level of masking of the latter on the former?
- What are the primary noise paths? What are the relative contributions of ambient, stethoscope, and patient noise pathways?
- Can we make effective use of commercially-available active and passive noise reduction techniques in reducing noise from these pathways? Which noise components are readily attenuated? Which are not?
- What is the best design configuration for an ANC prototype stethoscope specialized for the rotorcraft noise environment?
- How can we best test system performance and evaluate the utility of the device via psychophysical acoustic testing?
- What are the capabilities and limitations of the device? What is the recommended path to hardware and software optimization, and what is an appropriate plan for experimental verification and validation (V&V)?

By answering these questions under the Phase I effort, we will be in a position to outline a plan for Phase II system prototype development, experimental V&V, and demonstration of the system in an operational environment.

1.2 Technical Approach

Our Phase I technical approach to demonstrating feasibility of a hybrid active/passive noise canceling stethoscope consisted of five tasks:

1. Characterization of medevac stethorcope problems
2. Evaluation of commercial components for ambient path noise cancellation
3. Demonstration of passive isolation for stethoscope path noise reduction
4. Development and demonstration of custom ANC design for stethoscope/patient path noise cancellation

5. Recommendation of development path for full-scope research prototype

We first **characterized the medevac stethoscope problems** and evaluated solution options. We began with a characterization of the signal and noise components. Teaching tapes for heart sounds and lung sounds were reviewed, spectrum-analyzed and modeled. In addition, we made several recordings in the laboratory and characterized the resulting sounds in the frequency domain. The noise environment was characterized by recording in the cabin of a commercial Bell Jet Ranger 206B helicopter. Spectral analysis of the recorded signals was performed to evaluate the noise characteristics at different flight conditions. We then established expected baseline performance with conventional stethoscopes, and with a selected electronic stethoscope. Psychoacoustic testing was conducted to evaluate the clarity of the transducer sounds in a simulated rotorcraft acoustic environment, and the results analyzed to define the detectability of the heart sound as a function of ambient noise level.

We next **evaluated commercial components for ambient path noise cancellation**, via review and evaluation of commercially available components. We reviewed several available headsets incorporating ANC techniques for use in the commercial aviation market, and selected the Bose Aviation Headset for further study. We also reviewed several available electronic stethoscopes, and selected the Labtron stethoscope for further study. We characterized the acoustic transfer functions (for both signal and noise). We evaluated the headset capabilities for active and passive noise reduction. We also evaluated the stethoscope's sensitivity to heart/lung sounds, as well as sensitivity to unwanted ambient sound transduction. Using a simulation of the rotorcraft environment, we demonstrated the capabilities of the combined headset and electronic stethoscope in canceling the ambient path noise at the medic's ears.

Following the ambient path cancellation demonstration, we **demonstrated passive isolation for stethoscope path noise reduction**, via a laboratory evaluation. This involved characterizing the stethoscope sensitivity to ambient noise as a function of passive acoustic shielding, and its placement.

We then **developed and demonstrated a custom ANC design for stethoscope/patient path noise cancellation**, to enhance the signal to noise ratio at the transducer. This effort began with the development of a PC-based ANC design, using the rapid-prototyping language LabVIEW. A non-real-time engineering simulation was then developed to simulate post-processing of the contaminated stethoscope signal. Pre-recorded heart signals were contaminated with pre-recorded rotorcraft signals, and then processed by the PC-based ANC algorithm. Results demonstrated effective recovery of the original stethoscope signal. Following this, we demonstrated ANC operation with a dual-transducer configuration, with a primary stethoscope at the heart and a second reference stethoscope at a remote location on the trunk of the body that senses N_2 stethoscope/patient path noises for cancellation with the noise in the primary stethoscope. Post-processing by the ANC design again showed significant reduction in signal contamination, and effective recovery of the signal.

Finally we recommended a development path for a full-scope research prototype, based on the results of the Phase I evaluation effort. The development path includes an enhanced performance version of the Phase I design, implementation as a single-board package for real-time recovery of the stethoscope signal in rotorcraft noise, and demonstration and performance evaluation both in the lab and in flight, with a broad-based user population.

1.3 Summary of Phase I Results

The results of this Phase I effort demonstrate the feasibility of developing a hybrid active/passive noise canceling stethoscope for use in rotorcraft aeromedical evacuation. The major findings supporting this successful proof-of-concept demonstration can be summarized as follows.

An initial characterization of the problem was carried out to assess the impact of rotorcraft noise levels on conventional and electronic stethoscope sound clarity. A trained MD rated clarity as a function of noise level intensity, and it was found that ambient noise levels of 70-75 dBA or lower were required for unimpeded detection of heart sounds. Rotorcraft noise levels span the range from 80-90 dBA level for models with significant noise control treatment to 100-110 dBA levels for bare cabin interiors. Therefore, a stethoscope system designed for use in medevac rotorcraft, which typically have simple interior noise control treatments and noise levels in the 90-100 dBA range, will, on the basis of our psychoacoustic results, need to provide approximately 25-30 dB of effective reduction of the cabin noise, relative to the heart/lung sounds of interest.

The hybrid stethoscope system design evaluated in Phase I employed state-of-the-art passive noise control techniques and active noise cancellation (ANC) technology. The system consisted of an electronic stethoscope for sensing of heart/lung sounds, and an ANC headset to present the sounds to the medic for aural evaluation. For rotorcraft noise reaching the ear directly (N_1 noise), the commercially-available headset provided passive attenuation on the order of 10-20 dB above 200 Hz. Considered to be a high-quality design, the headset, made by the Bose Corp. for the general aviation market, provides additional active noise cancellation of 15-20 dB at low frequencies in the 40-300 Hz range, a range critical for listening to the generally low frequency heart/lung sounds.

Rotorcraft noise can also contaminate the transduction of heart/lung sounds by transmission into the body where it is picked up by the stethoscope, or by direct excitation of the stethoscope transducer (N_2 noise). The commercially-available electronic stethoscope used for the Phase I demonstration proved to be equally sensitive to acoustic noise acting on the case (the transducer *backside*), as on the diaphragm placed in contact with the body (the transducer *frontside*).

The Phase I study developed and demonstrated an ANC processor for stethoscope/patient path noise cancellation. A second stethoscope served as a noise reference, and was placed on the body at remote locations on the trunk where heart/lung sounds are diminished. An ANC processor was developed to process both signals, using the reference as a basis for adaptively estimating the noise in the primary, and then compensating the primary to recover a clear estimate of the uncontaminated heart/lung sound.

A non-real-time engineering simulation of the performance of the ANC algorithm yielded reductions of 10-15 dB below 600 Hz. A follow-on dual-transducer evaluation, using primary and reference stethoscopes on the body subjected to an ambient of rotorcraft noise, provided similar sound clarity enhancement, with noise reduced 10-15 dB below 350 Hz.

A quantitative assessment of relative noise contributions coming directly into the ear (N_1) and through the patient/stethoscope combination (N_2) showed both to be comparable in adversely affecting the listening process.

This Phase I effort has set the foundation for a follow-on program to develop an improved hybrid stethoscope system that combines both passive and active noise control techniques. A helmet meeting Army SPH-4B specifications would be proposed to provide 10-15 dB additional passive N_1 attenuation needed over the critical low frequency range. A modified electronic stethoscope transducer would be developed with reduced sensitivity to direct noise fields, using an enclosed bell cavity incorporating acoustic damping to minimize adverse effects of mechanical resonance of the stethoscope on the body. Finally, the ANC processor would incorporate advanced ANC algorithms and tuned parameters to better match the noise/transducer characteristics, and will be hosted on a single-board microprocessor, for compact implementation and operational flexibility.

In summary, our Phase I results have clearly established the feasibility of the proposed hybrid stethoscope system. The Phase I study was specifically structured to be narrow in scope, but sufficiently detailed to set the foundations for a full functionality hybrid noise canceling stethoscope.

1.4 Report Outline

Chapter 2 provides technical background on the hybrid ANC stethoscope system. Section 2.1 reviews the current technology on passive acoustic isolation. Section 2.2 then provides an overview of active noise cancellation and its application to acoustic problems.

Chapter 3 presents the overall design of the hybrid ANC stethoscope system. Section 3.1 presents the overall design concept, section 3.2 details the implementation of the stethoscope transducers, section 3.3 describes the ANC processor, and section 3.4 describes the hybrid noise cancelling headset.

Chapter 4 describes the system performance evaluation processes, and presents the evaluation results. Section 4.1 presents an overview of the evaluation environment. Section 4.2 characterizes the medevac stethoscope problem, based on the results of a psychoacoustic experiment. Sections 4.3, 4.4, and 4.5 present the evaluation results for ambient noise reduction via headsets, stethoscope noise reduction via passive isolation, and stethoscope/patient noise reduction via ANC processing. Section 4.6 summarizes the evaluation effort and results.

Chapter 5 concludes the report with a summary, conclusions, and recommendations for follow-on development.

2. BACKGROUND

This chapter provides technical background on the hybrid ANC stethoscope system. Section 2.1 reviews the current technology on passive acoustic isolation. Section 2.2 then provides an overview of active noise cancellation and its application to acoustic problems.

2.1 Passive Noise Reduction Technology

The theoretical basis for attenuation acoustic waves by solid structures involves the excitation of a panel wall or helmet by an incident airborne sound wave and the radiation of sound to the other side. The transmission loss, R is related to the transmission coefficient, τ.

$$R = 10 * \log \frac{1}{\tau} \tag{2.2-1}$$

Where τ is defined as the ratio of the transmitted acoustic power to the incident acoustic power (Beranek, 1960).

The design of structures, such as helmets for enhanced noise reduction involves a detailed understanding of the dynamic mechanical properties of materials and their configuration in practical designs. There is an extensive literature on this subject as shown by over 75 references in Beranek's Noise Control revised edition published in 1988. For example, sound transmission through sandwich constructions provides the design methodology for multiple barrier configurations (Ford et al, 1967). These designs, which are more effective against low frequency noise, generally include fibrous or porous acoustical materials in which the flow resistance is a measure of the sound attenuation (Nichols, 1947; Bies, 1963).

Thus, it is apparent that the technology of noise reduction by materials and structures is well understood and is being applied extensively in a wide variety of fields. In particular, the materials and structural design of sensors to minimize acoustic sensitivity is based on established design methodology. In the case of passive headsets or helmets to reduce airborne noise in the auditory system, a substantial body of design information and many commercial products are available. The of seating of helmets and headsets on the head is of primary importance to ensure proper sealing and prevention of sounds from flanking the device and entering the ear. The helmet is clearly more effective in this regard than a headset.

2.2 Active Noise Cancellation Technology

Active Noise Cancellation is a noise compensation technique that uses an auxiliary or reference input to provide information on the noise portion of the contaminated primary signal. From this *reference information* , an estimate of the noise is generated and then subtracted from the primary input to *cancel out* its additive noise portion. The success of the active nose cancellation technique mainly depends upon its capability of tracking the time-varying noise signal, since the technique is essentially equivalent to *bridge balancing*. Consequently, active noise canceling is typically performed by employing an adaptive process, which properly adjusts the parameters of the canceling signal filter, based on the reference and output signals.

Figure 2.2-1 depicts a typical Active Noise Canceled (ANC). We have a signal corrupted by an additive noise. The corrupted signal is picked up by a sensor in the primary channel. The noise, on the other hand, is picked up by a sensor in a separate reference channel. The primary and reference channels may have different transfer characteristics; this is represented by the block T in the reference channel. Using the reference noise and (N') and the recovered signal ($\hat{S}$) fed back from ANC output, the ANC generates estimates of the noise ($\hat{N}$), using a parameter optimizer to tune an adaptive filter. The estimated noise ($\hat{N}$) is then used to cancel the noise in the primary channel.

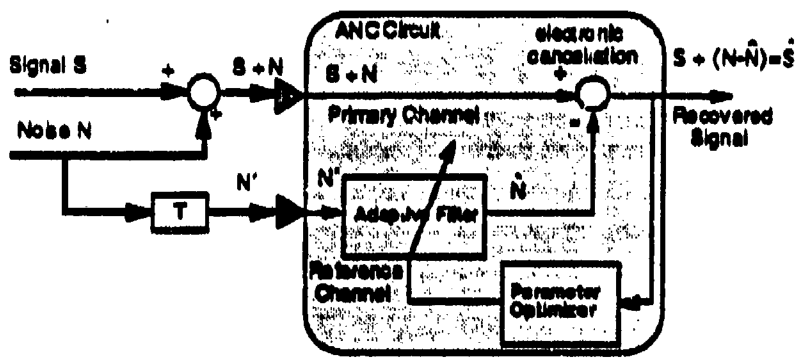


Figure 2.2-1: Active Noise Canceller

The major advantages of ANC are its adaptive capability, its stability, and its minimal contribution to signal distortion. Its adaptive capability supports the cancellation of input noises with unknown characteristics, which may change over time. Its stability is assured, since the cancellation signal will automatically turn itself off once no additional improvement in signal-to-noise ratio can be achieved. Finally, its contribution to distortion is generally lower than that of optimal signal filter configurations, since the ANC does not perform filtering (and thus distortion) operations on the primary (signal) path.

The concept of using a secondary source to generate a sound wave to cancel undesirable sound energy dates from the time of Lord Rayleigh (Rayleigh, 1984). A system for accomplishing the cancellation was first described in an early patent by Leug (1936). In Leug's concept a microphone detects the sound field and presents a signal to an electronic system that drives a speaker to generate sound out of phase with the offending sound. In Leug's work and subsequent early work (Wallace (1941), Olson (1956), and Conover and Gray (1957)), the focus was on the use of analog electronics that were adjusted manually for optimum performance. The concept of a self adaptive system, first introduced by Onoda and Kido (1968) in the late 1960's, was the precursor of today's self adaptive digital controllers.

Active noise control technology owes its growth in recent years to the combination of modern signal processing theory and the availability of cheap, high performance, digital signal processing hardware. In general one of two control strategies is utilized: feedforward or feedback. In recent years the strategy most commonly applied has been feedforward. Work in feedforward active control systems has included both theoretical and experimental studies of the control of sound in cabins and rooms (Nelson (1988), Ferren and Bernhard (1992), Elliott (1990), Lester and Silcox (1989), and Elliott (1990)), the control of sound in ducts (Munjal and Eriksson (1988), Eriksson (1987) and Hall (1990), the reduction of sound transmission through panels (Fuller (1989), and Pan and Hansen (1991)) control of sound radiation from structures (Clark and Fuller (1992)) and the increase of structural damping (Lee (1991)) to name just a few. In most cases the feedforward systems have utilized a number of variations on the "Filtered X" algorithm a specialization of the adaptive LMS algorithm originally developed by Widrow (Widrow and Stearns (1985)).

To function adequately a feedforward system requires a reference signal uncontaminated by the signal from the control actuators, a residual signal (i.e., the offending noise) and a filter whose response emulates the transfer function relating control actuator input to residual sensor output (i.e., the plant transfer function). The plant transfer function is obtained from direct measurement and a filter emulating it is usually obtained through application of the LMS algorithm. For the control of tonal noise, such as would result from the operation of rotating machinery, an uncontaminated reference signal is often readily available in the form of a tachometer signal, for example. For the control of broadband noise, such as one might encounter in a duct due to flow noise sources, an uncontaminated reference signal is more difficult to obtain. In such cases special *neutralization* feedback filters are employed to remove the control actuator signal from the reference sensors. When the noise to be canceled is tonal and there is an uncontaminated reference available, feedforward is the control strategy of choice, primarily because it is so easy to implement.

As a control strategy for noise cancellation, feedback has been much less commonly used than feedforward. Feedback is however commonly employed in vibration control problems (Sievers and von Flotow (1990), Meirovitch and Thangjitham (1990), and Watters (1988)). In many cases vibration control results in noise control and to a lesser extent in the control of sound in ducts (Hull (1990)). There is a broad technology base for the design of feedback control systems. A variety of control strategies are available such as pole placement, linear quadratic gaussian, and H-infinity (Maciejowski (1989)). All of these approaches require a mathematical model (typically a state space model) of the system to be controlled. Such a model is not often available. What one has instead are measured transfer functions and the state space mathematical model must be derived from these measurements. This is not an insurmountable difficulty but an additional complicating factor. In addition all of these design techniques are very complicated and it is easy to lose physical insight into the control process when applying them. Finally the feedback approaches do not adapt automatically to changes in the plant transfer functions but are designed instead to be "robust" to errors in the plant model. As a consequence, special procedures need to be developed to update the plant model as new measurements become available if the control system is to be fully adaptive.

A new approach, recently pioneered at BBN (Watters (1988)) called the compensator regulator approach, avoids many of the difficulties associated with the classical control approaches. It employs a compensator filter to remove the dynamics of the plant from the feedback loop and a regulator filter to focus the control effort in the frequency range of interest. In addition algorithms have been developed to determine the compensation filter coefficients directly from on-line measurements of the plant transfer functions. The approach has been implemented in a single input single output controller for controlling both tonal and broad band noise. In laboratory experiments the controller has achieved 6-10 dB of broad band control and 10-15 dB of narrow band control at frequencies below 100 Hz.

As discussed below, a review of these techniques has provided us with the basis for the design approach to be used in the ANC stethoscope processor. We discuss the particular approach in section 3 below.

3. SYSTEM DESIGN AND IMPLEMENTATION

This chapter presents the overall design of the hybrid ANC stethoscope system. Section 3.1 presents the overall design concept, section 3.2 details the implementation of the stethoscope transducers, section 3.3 describes the ANC processor, and section 3.4 describes the hybrid noise cancelling headset.

3.1 Design Concept

Figure 3.1-1 illustrates the overall design concept for the hybrid active/passive noise canceling stethoscope studied under the Phase I effort. Three major components comprise the system: electronic transducers with the fundamental function of sensing heart/lung sounds and noises, an ANC processor converting the contaminated transducer signals into clean heart/lung electronic signals sent to a headset at the ear, and a hybrid noise canceling headset to present the acoustic signals to the medical personnel.

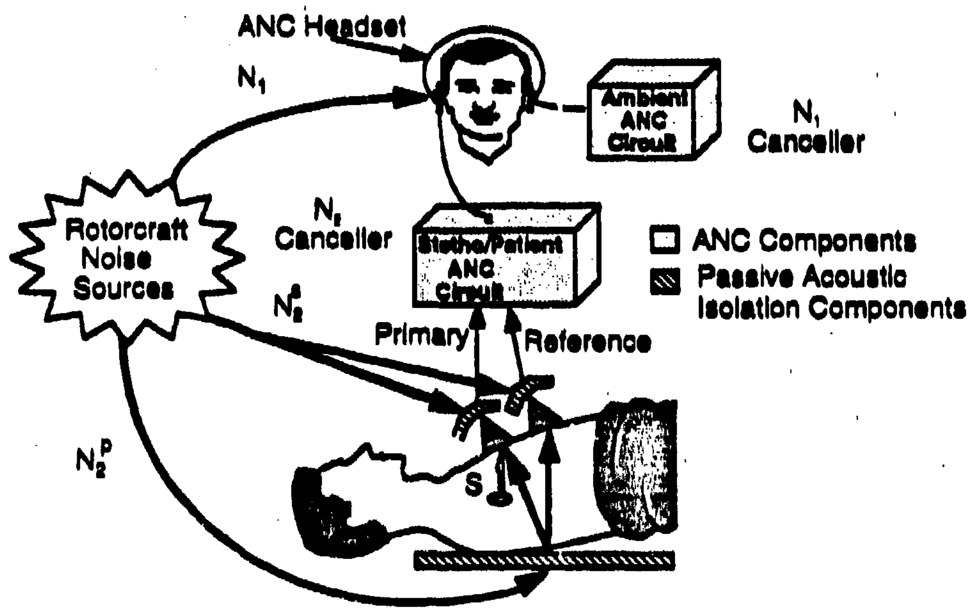


Figure 3.1-1: Hybrid Active/Passive Noise Canceling Stethoscope Design Concept

The patient is monitored via a dual-stethoscope system as shown in the figure. A primary transducer is used to pick up the desired heart/lung sounds of the patient, while a reference transducer is used to pick up the noise field impinging on the primary transducer. As described earlier, and as illustrated in the figure, the primary transducer is acted upon by a stethoscope noise component (N_2^s) and a rotorcraft-correlated patient component (N_2^p). In have shown both of these noise sources impinging on both the primary and reference stethoscopes, while little or no heart/lung signal is picked up by the reference itself. Note also that we have indicated the use of passive acoustic isolation, both to reduce ambient noise (N_2^1) acting on the stethoscope transducers (both primary and secondary), as well as passive acoustic isolation to isolate the patient from the noise field (N_2^2), as much as is practical in the aeromedical evacuation environment.

The ANC processor is the second component in the system and is shown in the figure as processing both the primary and reference signals generated by the two stethoscope transducers. The ANC processor uses conventional ANC techniques to recover the heart/lung signal from the noise-contaminated primary, via use of the reference signal to estimate the signal-contaminating noise as it varies over time. The recovered signal is then sent to the ANC headset for auditory presentation to the medic.

The ANC headset is the third component in the system and provides the medic with the auditory presentation of the critical patient sounds, while simultaneously serving to reduce the *ambient* path noise (N_1) acting directly on the medic's auditory system. This is achieved by both passive and active noise control. The passive component provides for high frequency attenuation ($f>500$Hz, approximately), while the active component provides for low frequency cancellation ($f<500$Hz, approximately), primarily in the frequency range of interest defined by the heart/lung sounds.

3.2 Stethoscope Transducer

We reviewed a number of candidate commercially-available electronic stethoscopes for use in the system design; a summary of the basic properties of those reviewed is given in table 3.2-1. The Labtron Electronic Stethoscope was selected early in the project because of its relatively low cost. We later became aware of the Electroscope model, an even more economical choice which deserves consideration in any follow-on effort devoted to transducer design and/or modification.

Table 3.2-1: Electronic Stethoscope Candidates

Manufacturer	Model	Price ($)	Notes
Burdick	PC-100	300.00	3 separate units: mic pickup, preamp, stethophone
3M Health Care Group	Littman Graphic Auscultation System	3000.00	Conventional acoustic stethoscope driving mic pickup, amp, and recording device
Graham-Field Inc.	Labtron Electronic Stethoscope	250.00	- Single package for mic, amp, stethophone - Selectable bandpass L: 20 to 200 Hz H: 20 to 2000 Hz
Lumiscope Co.	ElectroScope	100.00	Same as Labtron

The Labtron Electronic Stethoscope is illustrated in figure 3.2-1a. Its performance was evaluated as a transducer of heart and lung sounds and also in generating unwanted response to ambient acoustic noise in the surrounding environment. A transfer function for the Labtron, in the form of the ratio of output voltage for an input acoustic signal is shown in figure 3.2-1b, for two configurations.

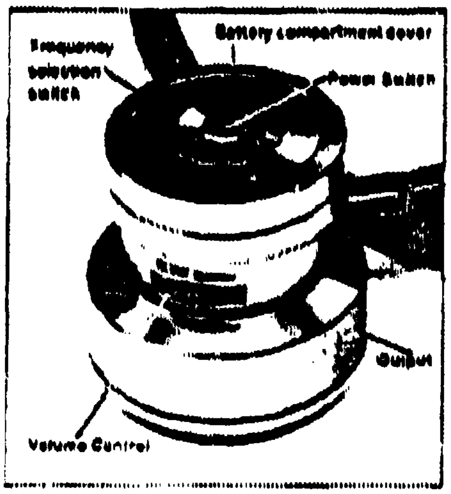


Figure 3.2-1a: Labtron Electronic Stethoscope

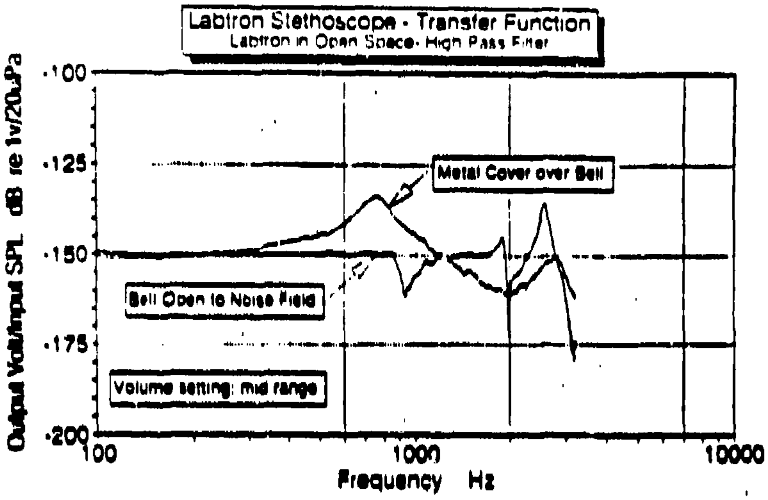


Figure 3.2-1b: Labtron Transducer Transfer Function

With the diaphragm open to the surrounding acoustic noise, the frequency response is flat in the frequency region below 800-1 kHz. This is the important region for listening to heart and lung sounds, with the heart sounds requiring sensitivity at the lower end of this range. The peaks and dips at high frequencies are due to internal resonance's with the structure and cavities of the stethoscope.

With the diaphragm covered with a rigid metal disc, the measured output is the result of the sensitivity of the transducer to the surrounding noise field on the *backside* of the unit. At low frequencies, the levels are the same as for the open diaphragm configuration, indicting that there is acoustic access to the sensing microphone within the stethoscope from the *backside* of the unit. Access is presumably through openings in the case for the filter and volume settings and the on/off button. This is undesirable for the rotorcraft application where the loud cabin noise levels would result in large N_2^S levels in the stethoscope output.

Two approaches can be used to reduce this unwanted contamination of the heart/lung sounds by the cabin noise: passive acoustic isolation of the transducer backside, and ANC processing of the transduced signal.

The purpose of transducer acoustic isolation is to reduce the stethoscope noises N_2^S picked up by the transducer. Since the stethoscope path noise mainly enters the system through the mechanical transducer, we used simple passive sound baffling material to build an isolation layer around the transducer as shown in figure 3.2-2. We recognize that passive isolation will only be effective for the mid-to high-frequency ambient noise impinging on the transducer, and that low-frequency noises may serve to mask out the heart/lung sounds to some extent. However this is a relatively low-cost modification that can gain us a significant reduction in the stethoscope noise N_2^s and lead to a further enhancement in signal detectability.

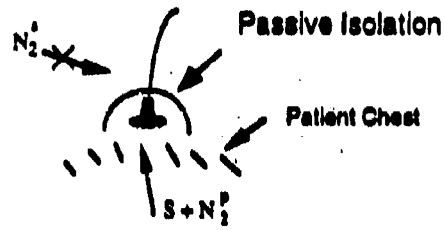


Figure 3.2-2: Stethoscope Path Design: Passive Acoustic Isolation

In section 4.3 below, we describe our approach to passive isolation of the stethoscope transducer, and the results obtained from preliminary experimental acoustic transfer function measurements.

3.3 ANC Processor

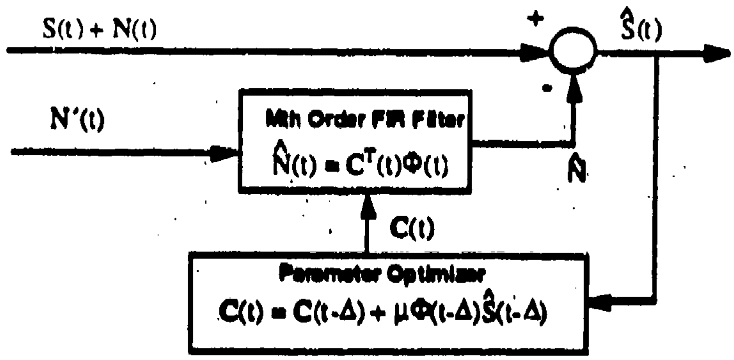
The Phase I design for the ANC processor adopts the classical noise canceller structure presented by Widrow and his colleagues (Widrow and et al (1975)), wherein a Finite Impulse Response (FIR) adaptive filter is used in the feedforward path to generate the noise canceling signal, and a Least Mean Squares (LMS) optimization algorithm is used to adjust the filter parameters based on the feedback error signal, as illustrated in figure 3.3-1.

The LMS algorithm is the oldest, and the most universally applicable algorithm (Stearns (1988), Widrow and et al (1975), Widrow and Stearns (1985), Soo and Pang (1991)). The rationale behind the algorithm can be summarized as follows:

As shown in the figure, the recovered signal $\hat{S}$ is the difference between the primary signal $[S(t) + N(t)]$ and the output of the FIR filter $C^T(t)\Phi(t)$, or:

$$\hat{S}(t) = S(t) + N(t) - C^T(t)\Phi(t) \tag{3.3-1}$$

where $C(t)$ is the coefficient vector and $\Phi(t) = [N'(t), N'(t-\Delta t), \ldots, N'(t-M\Delta t)]^T$ is an M-th order noisy signal vector. Squaring the above equation yields:



where $\Phi(t) = [N'(t), N'(t-\Delta), ..., N'(t-M\Delta)]^T$

Figure 3.3-1: Widrow Implementation of ANC

$$\hat{S}^2(t) = S^2(t) + N^2(t) + C^T(t)\Phi(t)\Phi^T(t)C(t) + 2S(t)N(t) - 2S(t)C^T(t)\Phi(t) - 2N(t)\Phi^T(t)C(t) \tag{3.3-2}$$

Assuming that S(t) and N(t) are statistically stationary and uncorrelated, we take the expected value of the (3.3-2) to obtain

$$\begin{aligned} E[\hat{S}^2(t)] &= E[S^2(t)] + E[N^2(t)] - 2E[N(t)\Phi^T(t)]C(t) + C^T(t)E[\Phi(t)\Phi^T(t)]C(t) \\ &= E[S^2(t)] + E[\tilde{N}^2(t)] \end{aligned} \tag{3.3-3}$$

Since $E[\Phi(t)\Phi^T(t)]$ is positive semidefinite (usually positive definite), there exists an optimal choice of C(t) that minimizes the mean-square error $E[\tilde{N}^2(t)]$. The LMS algorithm is a practical way for finding the approximate solution to the optimal C(t), by using the steepest descent method. According to this method, the *next* coefficient vector $C(t + \Delta t)$ equals the *current* coefficient vector C(t) plus a change proportional to the negative gradient of the power of the recovered signal:

$$C(t + \Delta t) = C(t) - \mu\nabla(t) \tag{3.3-4}$$

The parameter μ is the *convergence factor* that controls stability and rate of convergence, and $\nabla(t)$ is the true gradient of $E[\hat{S}^2(t)]$.

The LMS algorithm estimates an instantaneous gradient in a crude but efficient manner by assuming that $\hat{S}^2(t)$, the square of a single sample, is an estimate of its mean-square value, so that by differentiating $\hat{S}^2(t)$ with respect to C, we obtain:

$$\hat{\nabla}(t) = \frac{\partial \hat{S}^2(t)}{\partial C} = 2\hat{S}(t)\frac{\partial \hat{S}(t)}{\partial C} = -2\hat{S}(t)\Phi(t) \tag{3.3-5}$$

Substituting this estimate into the true gradient in (3.3-4), we obtain the LMS algorithm

$$C(t+\Delta t) = C(t) + 2\mu\hat{S}(t)\Phi(t) \tag{3.3-6}$$

The LMS algorithm has very good convergence properties, is efficient and simple, and can be used for both stationary and non-stationary signals. Detailed discussions of these properties can be found in Gardner (1987), Goodwin and Sin (1984), Stearns (1988), Widrow and et al (1975), Widrow and Walach (1984), Widrow and Stearns (1985), and Gardner (1987).

To assess the noise reduction capability of the active noise canceler, we tested the ANC algorithm in a simulated rotorcraft noise environment. In the testing, identical recorded rotorcraft noises were sent to the primary and reference channels of the ANC, while no heart signal was presented to the primary channel. The recovered signal after cancellation should thus clearly indicate the maximum noise reduction capability of the ANC algorithm.

Figure 3.3-2a shows the time history of the recovered signal with the noise canceler turned on in the middle of the time history, while figure 3.3-2b shows the spectra of the primary and recovered signals. The difference between the primary and the recovered signals indicates a noise reduction greater than 30 dB over 20-100 Hz, and 10-20 dB over 100-300 Hz, and no reduction above 300 Hz. These results imply that ANC is indeed capable of providing the required noise reduction at low frequencies, but not at the high frequencies, which can be dealt with using passive isolation.

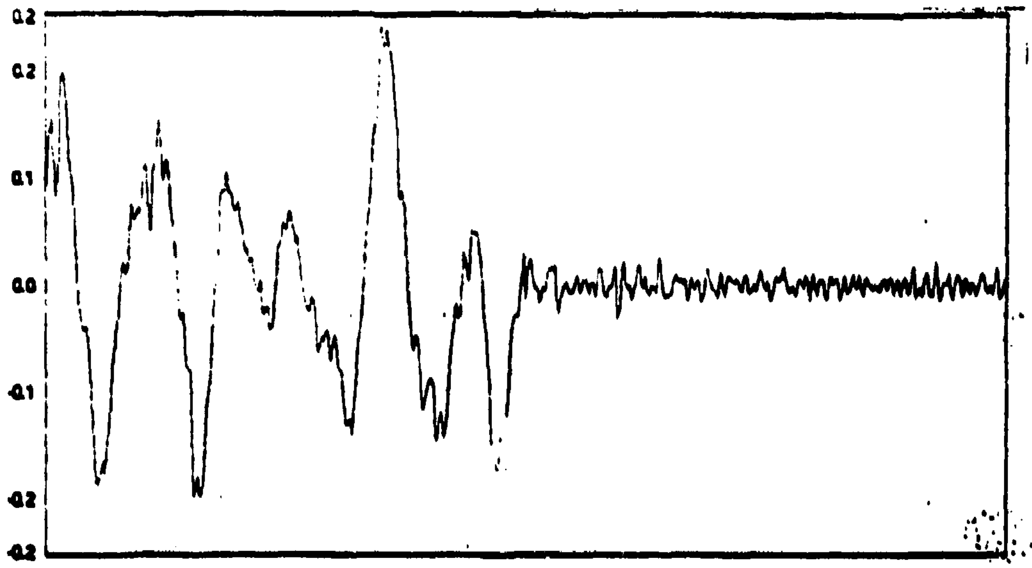


Figure 3.3-2a: Time History of Recovered Signals

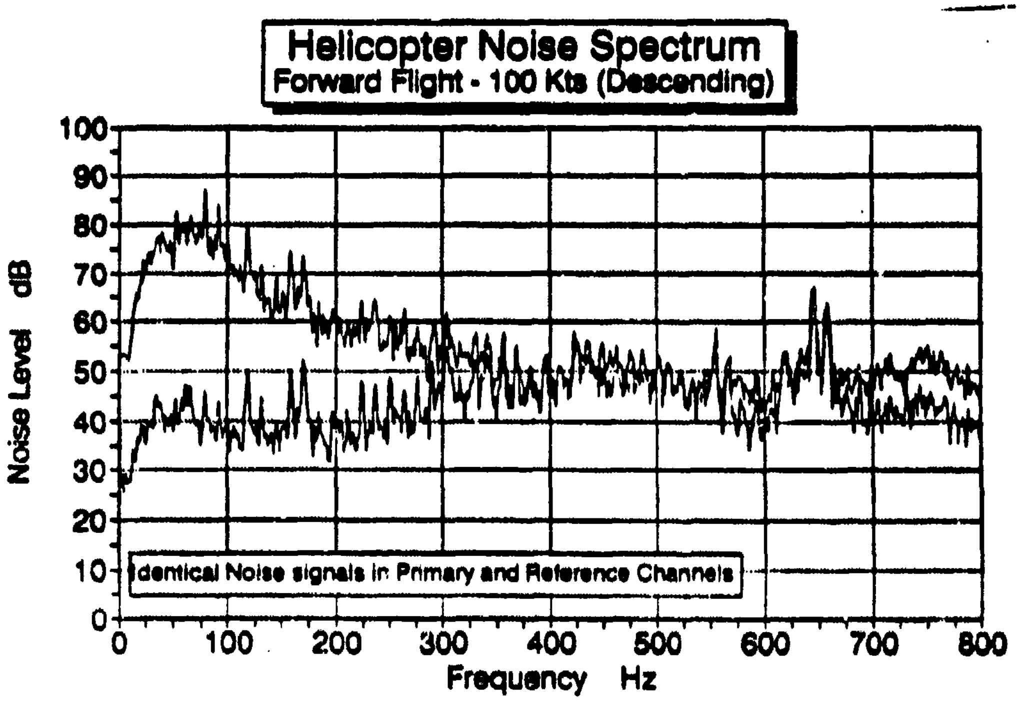


Figure 3.3-2b: Spectra of Primary and Recovered Signals

3.4 ANC Headset

We reviewed a number of candidate commercially-available General Aviation (GA) ANC headsets for use in the system design; a summary of the basic properties of those reviewed is given in table 3.4-1. The Bose Aviation Headset was selected early in the project, in spite of its expense, primarily because it is widely recognized by GA users as the leader in effectiveness at high noise levels, and is comfortable, and reliable.

Table 3.4-1: Active Noise Cancellation Headset Candidates

Manufacturer	Model	Passive Reduction (dB)	Active Reduction (dB)	Price ($)
Bose Corp	Aviation Headset	20 (approx)	12-15	1000
David Clark	DCNC Headset	24	10-15	1000
Evolution*				300
Telex	ANR Headset	24	10-15	500
	ANR 4000	21	15	1000

*Out of Business (?) 8/93

The Bose Aviation Headset incorporates both passive reduction of the high-frequency noise components and active cancellation of the low-frequency noise components. Figure 3.4-1 illustrates system operation in our application.* There are two *inputs* to the headset: the heart/lung sound S and the ambient noise N_1. The heart/lung sound S is picked up by the stethoscope and converted into an electrical audio input to the headset. In parallel, the ambient rotorcraft noise N_1 is first reduced *passively* by earcup acoustic isolation to yield a low-frequency noise component N_1^{Low} *inside* the earcup. This, in turn is then *actively* canceled acoustically by adding a signal to the headset speaker that approximates the negative of N_1^{Low}. This is achieved by measuring the acoustic signal inside the earcup via an earcup microphone, and then differencing this electrical signal with the heart/lung electrical signal, to generate a residual signal ε. The ANC circuits then attempt to zero out this signal, by generating a feedback to bias off the headset speaker. Under ideal conditions this bias exactly equals N_1^{Low} to ensure acoustic cancellation of the nose at the medic's ear.

* For simplicity in this diagram we have not included noise contamination of the stethoscope signal nor have we shown ANC post-processing of the stethoscope signal. The assumption here is that the heart/lung signal S is "clean".

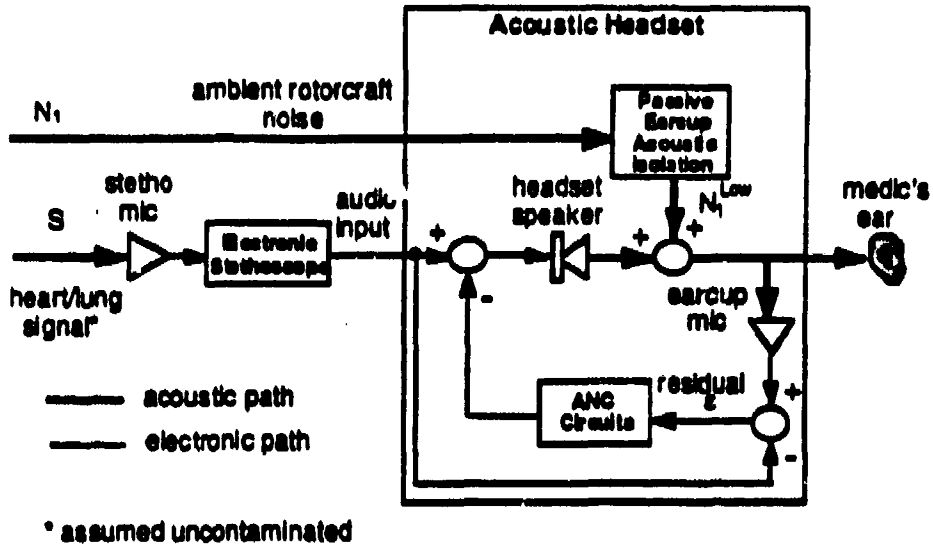


Figure 3.4-1: Ambient Path Design: Bose Aviation Headset

We measured the headset performance in a white noise environment with a small microphone at the ear for configurations with no headset, with the headset in place without the ANC on, and with the ANC on. Figure 3.4-2a shows passive noise reduction ability, obtained with the ANC circuit turned off. We see little reduction below 200 Hz, 10-20 dB reduction in the 200-600 Hz range, and greater than 20 dB reduction at higher frequencies. Figure 3.4-2b shows the *additional* noise reduction afforded by the ANC circuitry, obtained by comparing noise levels with and without the ANC on. We see 10-20 dB reductions in the key 40-400 Hz band where both heart and lung sound contain significant signal energy, as we discuss in the next section. A comparison of both figures shows that we can expect combined passive and active ambient noise reduction levels of 10-35 dB in this frequency band.

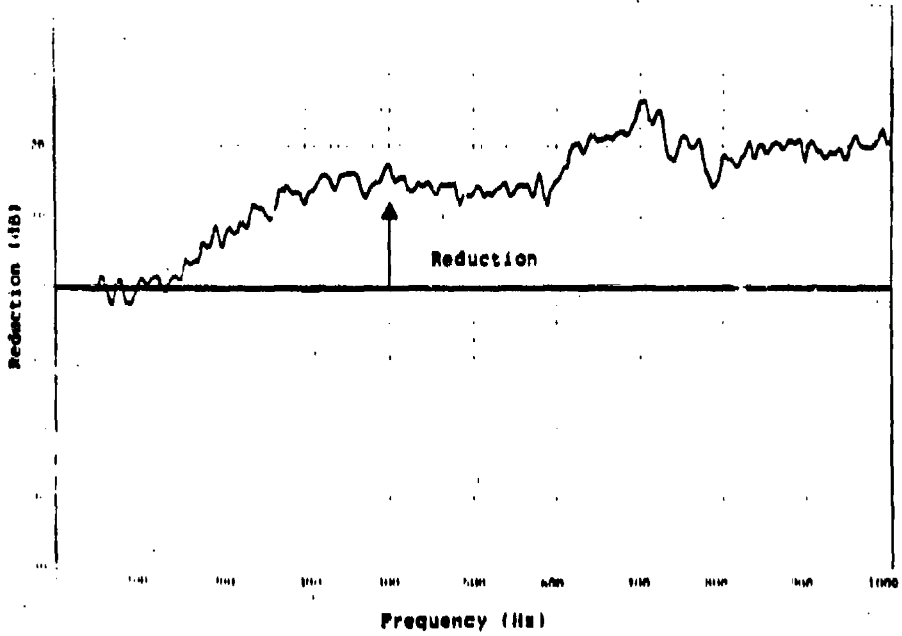


Figure 3.4-2a: Passive Noise Reduction Performance Using Bose Headset

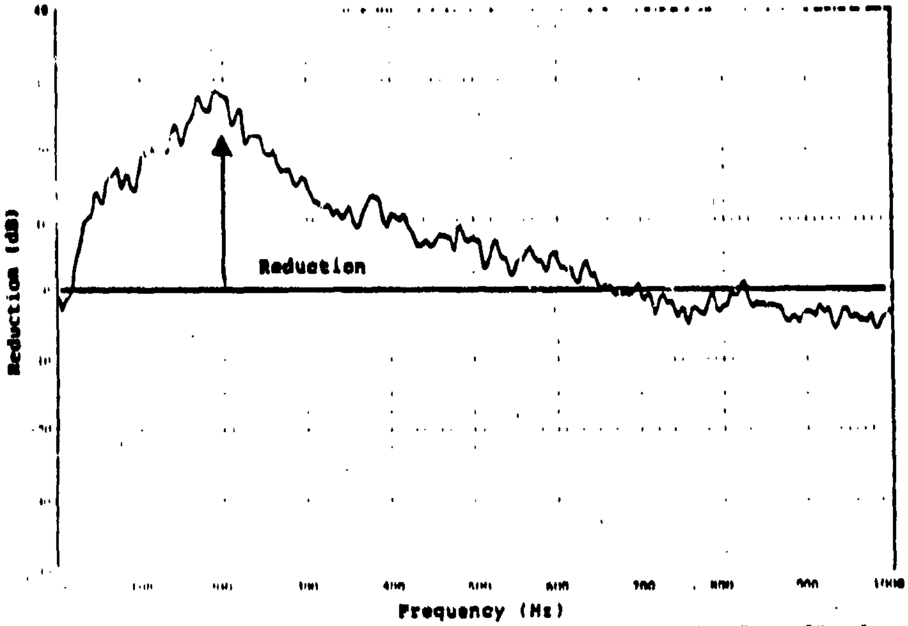


Figure 3.4-2b: Active Noise Reduction Performance Using Bose Headset

4. SYSTEM PERFORMANCE

This chapter describes the system performance evaluation processes, and presents the evaluation results. Section 4.1 presents an overview of the evaluation environment. Section 4.2 characterizes the medevac stethoscope problem, based on the results of a psychoacoustic experiment. Sections 4.3, 4.4, and 4.5 present the evaluation results for ambient noise reduction via headsets, stethoscope noise reduction via passive isolation, and stethoscope/patient noise reduction via ANC processing. Section 4.6 summarizes the evaluation effort and results.

4.1 Problem Characterization

4.1.1 Signal and Noise Characteristics

To characterize the scope of the problem, and to generate a signal/noise database for later system test and evaluation, we obtained several recordings of heart, lung, and rotorcraft sounds. Heart sounds were obtained from a cardiology instructional tape recording and by transducing/recording heart sounds in the lab. Likewise, lung sounds were obtained from a lung sound instructional tape recording, and by transducing/recording lung sounds in the lab. Finally, rotorcraft cabin sounds were recorded in flight, in a Bell Jet Ranger 206B, at a number of different flight conditions, to provide a range of in-cabin acoustic signatures.

Figure 4.1-1a shows a short time history of heart sounds obtained from the cardiology instructional tape. Figure 4.1-1b shows the corresponding power spectrum over the 0-800 Hz band. Note how the power is concentrated in the 40-400 Hz range.

Figure 4.1-2a shows a comparable time segment of rotorcraft cabin noise obtained from our recordings made at a 100 kt cruise condition. Independent noise level measurements made during the recording showed a sound pressure level of approximately 95 dBA. Figure 4.1-2b shows the power spectrum of the recorded noise, over the 0-800 Hz band. Note how most of the power is concentrated in the 40-400 Hz band, exactly where our signal power is concentrated.

To illustrate the magnitude of the problem facing the medic in using a stethoscope in the rotorcraft cabin, figure 4.1-3a shows how the clean heart signal looks when contaminated by the rotorcraft noise of figure 4.1-2a.

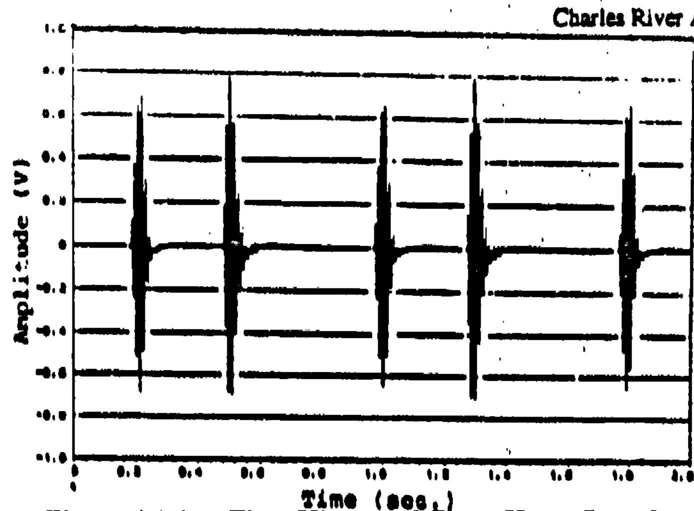


Figure 4.1-1a: Time History of Clean Heart Sound

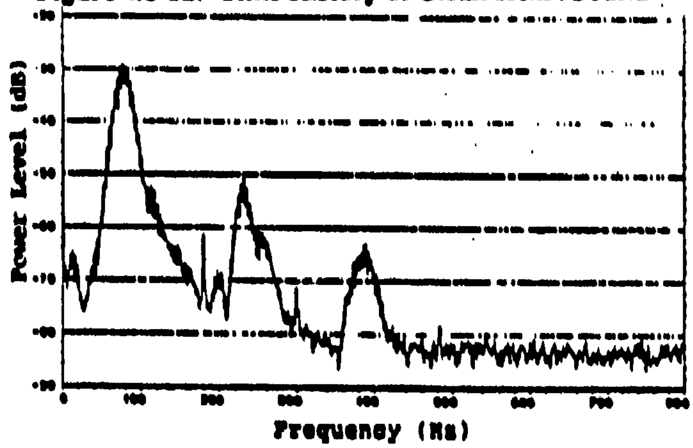


Figure 4.1-1b: Power Spectrum of Clean Heart Sound

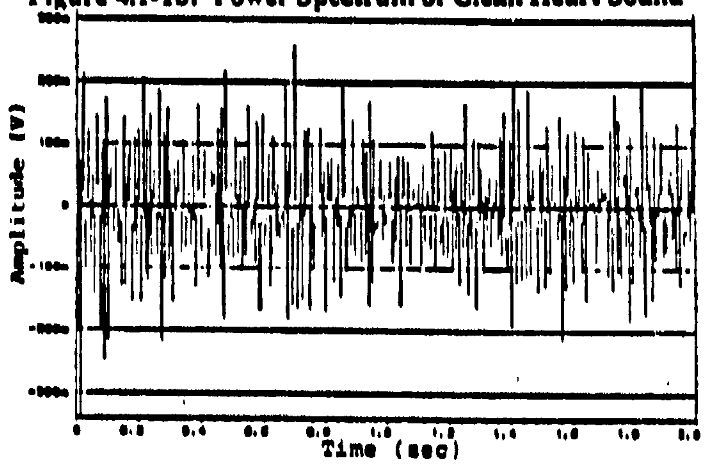


Figure 4.1-2a: Time History of Rotorcraft Noise

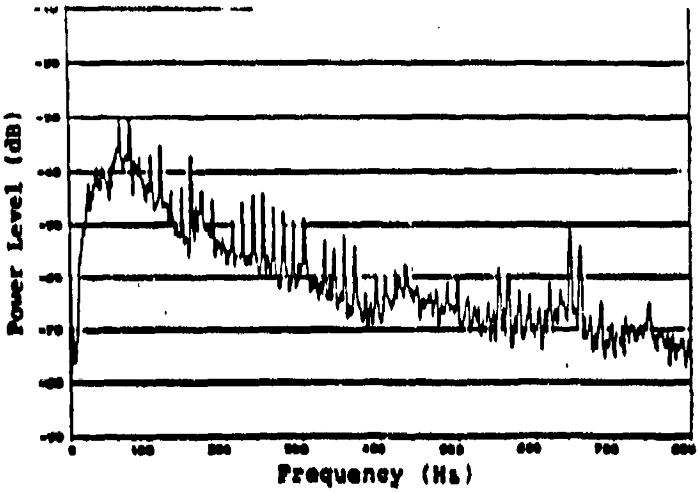


Figure 4.1-2b: Power Spectrum of Rotorcraft Noise

Although some of the beats can be seen in this trace, the acoustic signature is not at all clear. In fact, in listening to the recording used in generating the trace of figure 4.1-3a, the heart signals are totally swamped by the rotorcraft noise, so as not to be auditorily discernible. Figure 4.1-3b shows the corresponding power spectrum of the contaminated heart signal. Direct comparison with the clean heart sound spectrum shows how the ambient noise spectrum of figure 4.1-2b effectively eliminates the three spectral peaks characterizing the heart sound spectrum of figure 4.1-1b, yielding a spectral signature that more nearly approximates the noise itself.

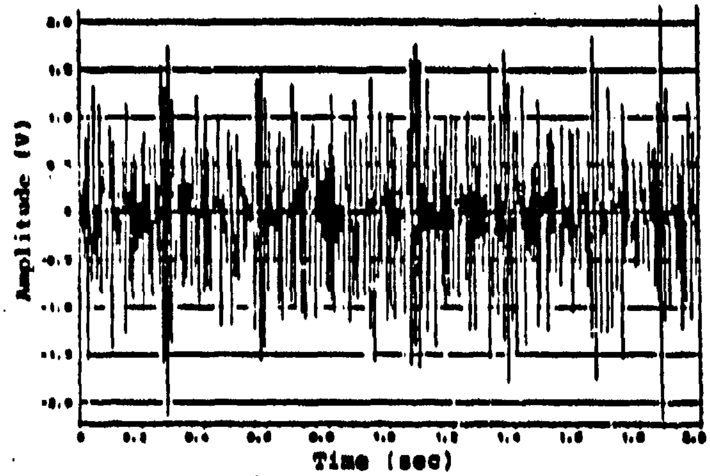


Figure 4.1-3a: Time History of Contaminated Heart Sound (95 dBA ambient)

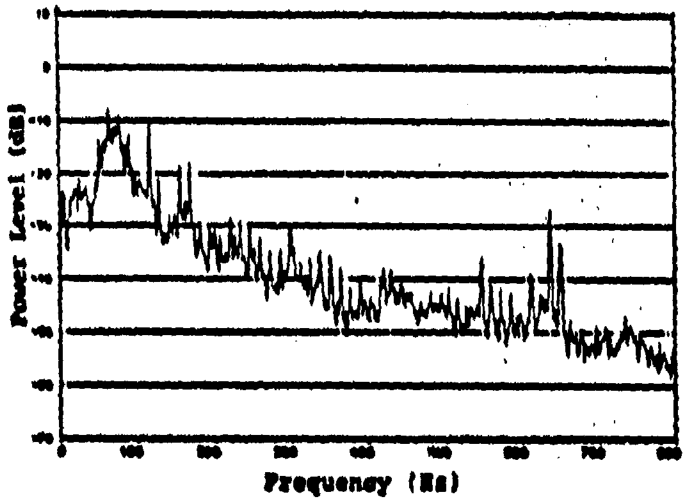


Figure 4.1-3b: Power Spectrum of Contaminated Heart Sound (95 dBA ambient)

4.1.2 System Performance Requirements

To determine the noise reduction requirements on a quantitative basis, we conducted psychoacoustic testing of stethoscope clarity. For the evaluation testing, a trained MD rated his ability to detect heart sounds in a background of simulated rotorcraft noise, generated by speakers in the laboratory, using either: 1) a conventional stethoscope; 2) an electronic (Labtron) stethoscope; or 3) a simple prototype of our proposed system, consisting of a Bose headset, an audio amplifier, and an electronic (Labtron) stethoscope transducer. Figure 4.1-4 illustrates the experimental setup, configured for evaluation of the third option, the simple prototype. A detailed list of the experimental equipment is given in Appendix A.

The MD listened to heart sounds while the background noise levels were varied. Stethoscope performance was evaluated using a rating scale of 0 to 4, with 0 corresponding to a subjective evaluation that the heart sounds were completely masked by the rotorcraft noise and 4 corresponding to the case where the rotorcraft noise was sufficiently low so as to not interfere at all with the MD's ability to listen to the heart sounds. The ratings for different stethoscopes were plotted versus an A-weighted single number sound pressure level for the noise that was measured at the ear location.

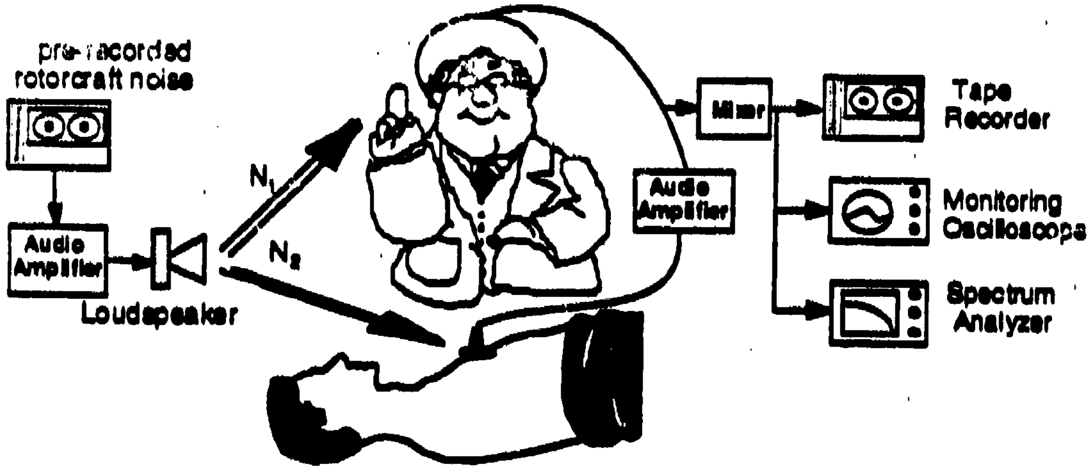


Figure 4.1-4: Psychoacoustic Experiment

The experimental results are shown in figure 4.1-5, which plots performance rating as a function of ambient noise level, for five different listening set-ups: a "standard" stethoscope, a Littman Cardiology stethoscope, the Labtron stethoscope used with conventional earpieces (once with the low-pass (lp) filter option set, and once with the high-pass (hp) filter option set), and the Labtron/amplifier/headset combination. As seen by the downward trend of all the curves, performance ratings drop rapidly with increasing ambient noise levels. Low interference is seen at 65 dBA ambient noise level (typical office conditions), whereas the heart sounds cannot be heard at a 90 dBA ambient noise level.

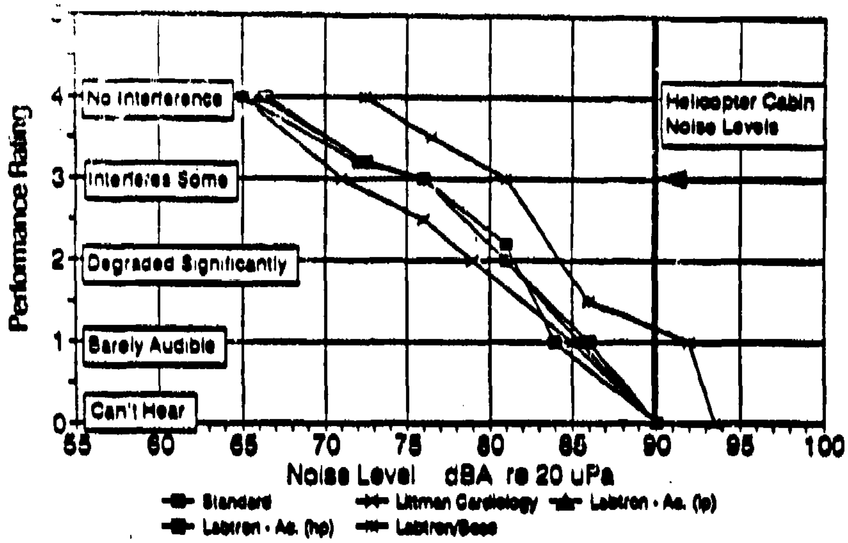
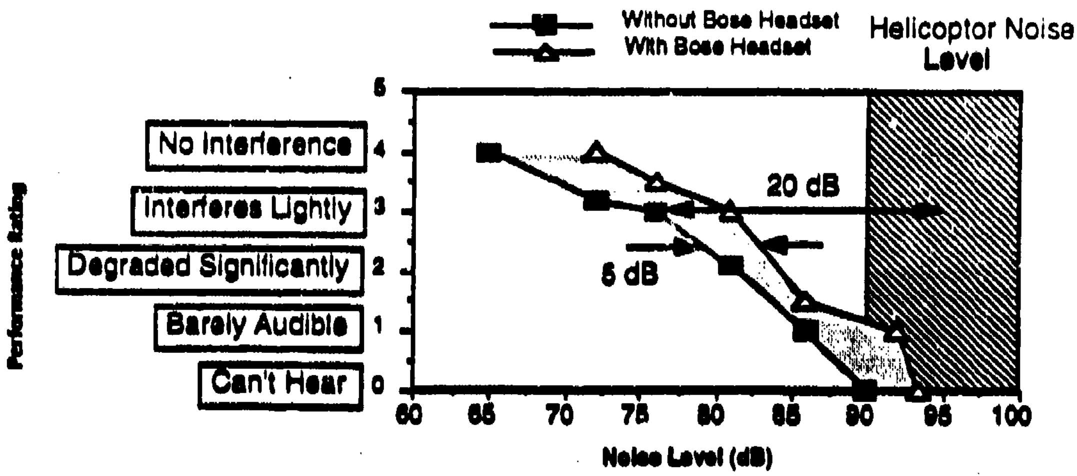


Figure 4.1-5: Subjective Ratings of Stethoscope Performance as a Function of Rotorcraft Noise

If we focus on the four conventional/electronic stethoscope curves of the figure, we see that detection at Level 3 with little interference requires A-weighted sound pressure levels no greater than 70-75 dBA. Typical rotorcraft cabin noise levels are in the 80-90 dBA range for models with standard interiors, and in the 100-110 dBA range for models without interior treatment. Assuming a typical 95 dBA level, as we measured in the Bell 206B, and requiring Level 3 sound quality, the data then implies that we must provide an overall noise reduction of 20-25 dBA; for untreated cabins we will need to provide reductions of 30-35 dBA.

This requirement is based on the four psychoacoustic data curves of figure 4.1-5 characterizing conventional/electronic stethoscope listening. If we compare all four as a group, with the *single* curve obtained with the headset/amplifier/transducer combination, we can identify *which* noise component to focus on: the ambient N_1, the stethoscope N_2^s, or the patient N_2^p.

Figure 4.1-6 presents the same psychoacoustic data but this time shows the four conventional/electronic configurations as one curve (filled boxes) and the headset/amplifier/transducer combination as the other curve (open triangles). Although the Bose headset is capable of a 15 dB reduction in ambient noise levels, the difference in the curves clearly shows only a 5 dBA reduction. What this implies, is that ambient noise (N_1) reduction is *not* sufficient, and attention *must* be paid to a significant contribution in noise level at the patient/transducer portion of the system (N_2).



4.1-6: Comparison of Subjective Performance Ratings With and Without Ambient ANC

On the basis of these results, we can estimate the relative contribution of the ambient and patient/stethoscope noises as follows. Let N_1 and N_2 denote the contribution of ambient and patient/stethoscope path noises in the overall noise. It is assumed that $N_2 = KN_1$, where K is the relative ratio between ambient and patient/stethoscope noises, and is to be found on the basis of this analysis. The overall noise level before any reduction thus equals

$$N_1 + N_2 = K(1 + N_1) \tag{4.1-1}$$

From the experiment, we know that a 5 dB overall noise reduction is achieved, which corresponds an overall noise N_1 reduction ratio $\gamma = 0.56$. In other words, after noise reduction we have an overall noise level

$$\gamma(N_1 + N_2) = 0.56K(1 + N_1) \tag{4.1-2}$$

This overall 5 dB noise reduction includes a 15 dB reduction in ambient noise, which corresponds an ambient noise reduction ratio $\alpha = 0.18$, and zero reduction in patient/stethoscope noise N_2, which corresponds to a patient/stethoscope noise reduction ratio $\beta = 1.0$. From the overall noise reduction equation

$$\alpha N_1 + \beta N_2 = \gamma(N_1 + N_2) \tag{4.1-3}$$

so that

$$0.18N_1 + KN_1 = 0.56(1 + K)N_1 \tag{4.1-4}$$

which leads to a relative ratio $K = 0.86$.

Substituting this estimated relative ratio into (4.1-3), we obtain a constraint equation that relates the relative noise reduction ratio requirements between ambient and patient/stethoscope paths to the required *overall* noise reduction ratio:

$$\alpha + 0.86\beta = 1.86\gamma \qquad (4.1\text{-}5)$$

Figure 4.1-7 plots the relative noise reduction constraint equation in dB levels. From the figure, we can see in the rotorcraft noise environment that it is impossible to achieve the required level of overall noise reduction using only ambient noise (N_1) reduction or patient/stethoscope noise (N_2) reduction. As a matter of fact, at least 15 dB reduction is needed at either point to generate an overall 20 dB of noise reduction. For a much noisier environment (30 dB requirement), at least 25 dB at both points is required. Moreover, since the ambient and patient/stethoscope noises contribute almost equally to the overall noise, a good system design would call for each point to provide a level of noise reduction equal to that of the overall noise reduction requirement.

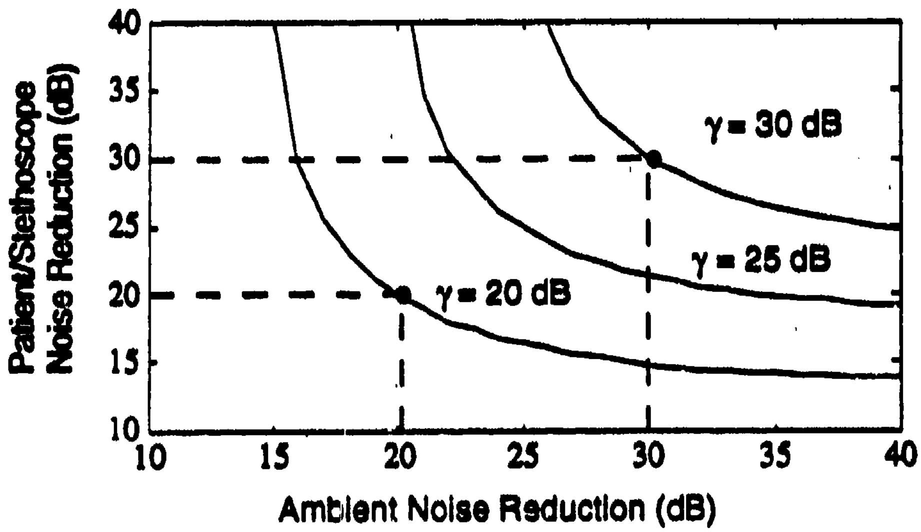


Figure 4.1-7: Noise Reduction Requirements Between Ambient (N_1) & Patient/Stethoscope (N_2) Paths

4.2 Evaluation of Ambient Noise Reduction in Rotorcraft Noise Environment

The evaluation of ambient noise (N_1) reduction capability in the rotorcraft noise environment was conducted using the same measurement setup as that used in the psychoacoustic experiment just described, except that no heart sound signal was sent to the Bose headset. In this evaluation, sound level was measured inside and outside of the Bose headset earcup, so that the difference reflects the level of ambient noise reduction.

Figure 4.2-1 shows the effectiveness of the Bose headset for ambient noise reduction. Three ear sound spectra are obtained using pre-recorded rotorcraft noises, corresponding to three cases: without the Bose headset, with the Bose headset but without ANC, and with the Bose headset with the ANC on. Confirming our earlier measurements, the passive isolation (with Bose headset on but without ANC) reduces the noise by 10 to 20 dB at high frequencies (> 200 Hz) but shows little or no effect on low frequency noise (< 200 Hz). The ANC circuit provides us with an extra 15 dB ambient noise reduction in the 40-400 Hz band. Altogether, the ANC Bose headset is able to reduce, by both passive and active means, ambient noise by 10 to 35 dB over the key 40-400 Hz frequency band.

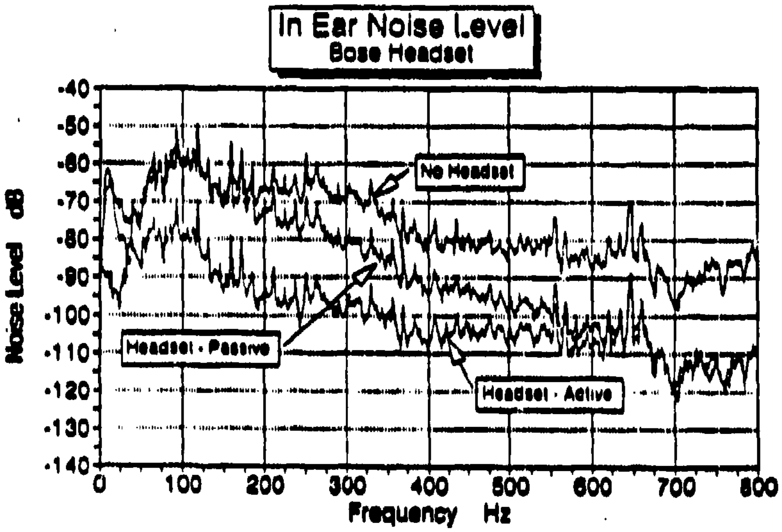


Figure 4.2-1: Effectiveness of Bose Headset for Ambient Noise Reduction

4.3 Evaluation of Patient/Stethoscope Noise Reduction via Passive Isolation

To evaluate the effect of passive isolation on patient/stethoscope noise (N_2) reduction, we built an acoustic isolation cover for the transducer component. The effectiveness of the isolation on noise reduction was evaluated by comparing the output of the transducer with and without isolating the transducer, while driving the transducer *backside* with the ambient noise. From figure 4.3-1 we can see that the passive isolation cover can reduce noise by more than 5 dB in the medium and high frequency ranges, but has little effectiveness at low frequencies.

To achieve additional reduced backside sensitivity requires that the transducer bell housing be sufficiently rigid with no mechanical resonance's in the frequency range of interest, and have sufficient inertia to prohibit it from moving relative to the chest at low frequencies in response to the acoustic noise acting on the *backside* or case. Such motion would compress the bell cavity, generating a pressure signal that would be sensed by the microphone and output to the headset. Neither of these mechanical requirements on the design of the stethoscope transducer presents major difficulties, although implementing these *passive* noise reduction measures was beyond the scope of the Phase I study. Our effort, instead, focused on noise reduction achievements attainable by *active* means.

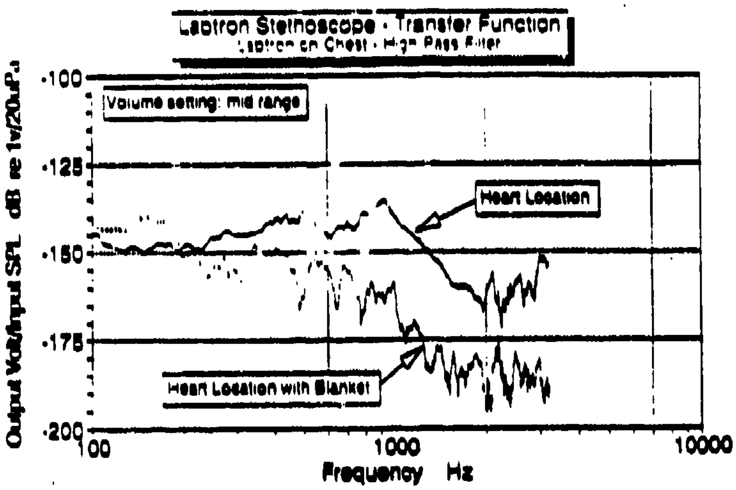


Figure 4.3-1: Effectiveness of Passive Isolation on Stethoscope Transducer

4.4 Evaluation of Effect of Patient/Stethoscope Noise Reduction via ANC Processing

To evaluate the utility of ANC processing for patient/stethoscope noise reduction (N_2), two types of testing were conducted: a non-real-time engineering test which supported basic algorithm development and evaluation, and a pseudo real-time dual-stethoscope test which closely simulated the actual operation of the ANC processor.

4.4.1 LabVIEW Platform for ANC Processor Implementation

The ANC processor was implemented using the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) in an IBM-compatible PC (Gateway 2000 486DX2/50E). LabVIEW, a product of National Instruments Corporation, is a major software tool used for the simulation of instrument performance, wherein an instrument is defined as a device that performs tasks such as generating, switching, measuring, transforming, and/or controlling input signals. Instruments characteristically have front panels that contain controls like knobs and switches to configure the measurement process, along with indicators like meters and lights to display signal values. Behind the front panel is an assembly of electronic components that performs the instrument's functions, such as converting a physical signal to an electrical one, and then converting that to a numerical value, etc. Instruments also typically have interfaces for communication with each other.

A virtual instrument (VI) in LabVIEW is a software construct that has characteristics of an instrument. In particular, it has a front panel that is displayed on the computer screen and operated via the keyboard and mouse; a program, in lieu of an assembly of electronic components, that performs the VI's function; and a calling interface for communicating with other VIs.

The actual implementation of the ANC processor needs analog-to-digital (A/D) converters that convert the transducer voltage signals to digital ones, a digital *circuit* that implements the ANC algorithm, and a digital-to-analog (D/A) converter that coverts the digital values to an output voltage signal, as shown in figure 4.1-1.

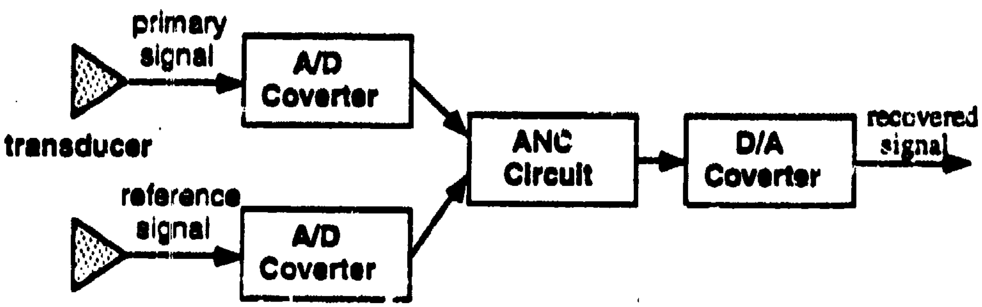


Figure 4.4-1: ANC Processor Architecture

In the LabVIEW development environment, the ANC processor is simulated via a *virtual* ANC processor hosted on an IBM-compatible PC, as shown in figures 4..4-2a and 4.4-2b. Three virtual instruments (VIs), one each for the A/D, ANC, and D/A blocks, are implemented to simulate the actual A/D, D/A, and ANC circuits. The primary and reference stethoscope transducer voltage signals are fed into the computer and processed via these three VIs to generate a recovered heart sound voltage signal.

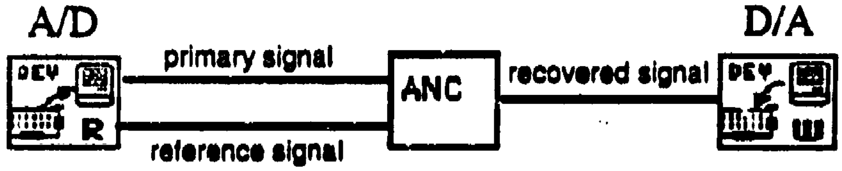


Figure 4.4-2a: LabVIEW VIs for ANC Processor

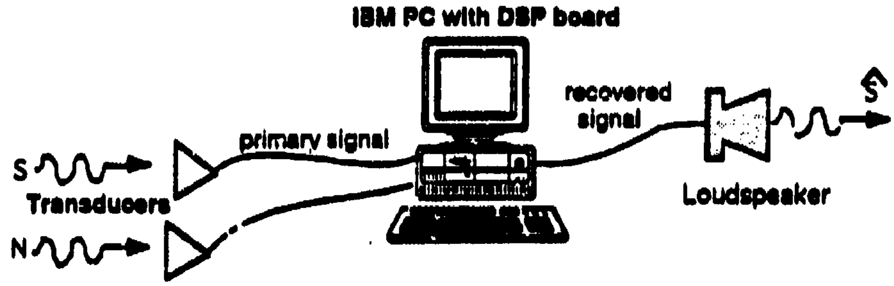


Figure 4.4-2b: Computer Host and Interface Hardware

Figure 4.4-3 shows the *front panel* of the ANC processor VI, as implemented in LabVIEW. Two input terminals are created to receive the digitized primary and reference signals. Two control variables, filter order M and convergence factor μ, are used for setting the finite impulse response (FIR) filter order and convergence factor in the Least Mean Squares (LMS) algorithm. An output terminal is created to send out the recovered digital signal.

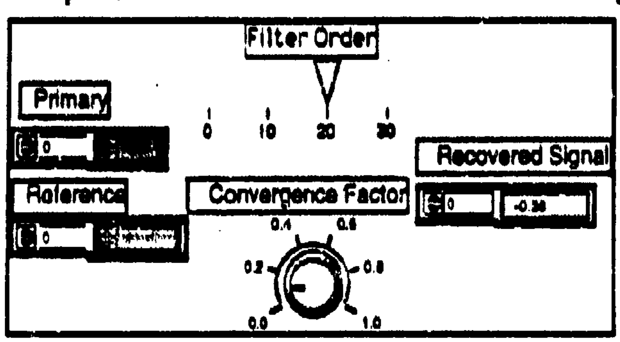


Figure 4.4-4: Front Panel of ANC Circuit

Figure 4.4-5 illustrates LabVIEW's block diagram of the ANC processor VI. The front panel input terminals, output terminal, and controls are represented by the rectangular blocks adjacent to their labels. The LMS algorithm and FIR filter are implemented via LabVIEW operators as shown in the figure.

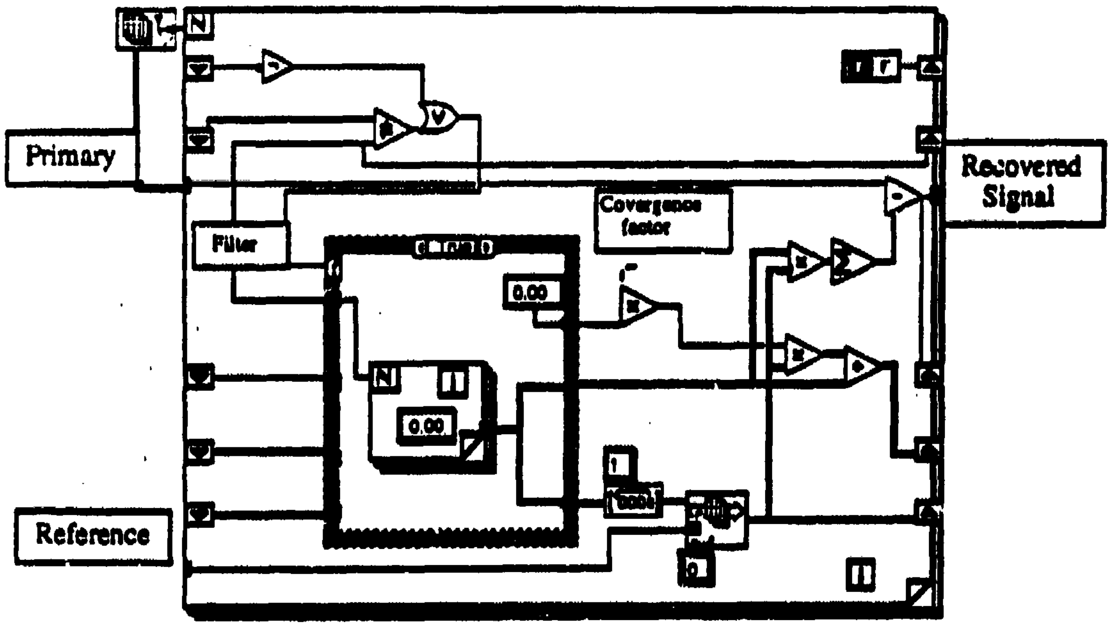


Figure 4.4-5: LabVIEW Diagram of ANC Circuit

4.4.2 Engineering Simulation of ANC Processing

Figure 4.4-6 illustrates the test setup for the engineering simulation. Pre-recorded clean heart and rotorcraft noise signals are sampled and transformed into digital signals through two A/D transformers. The noise signal is amplified (or reduced) according to the test condition, and is used as the reference signal. The primary signal is generated by adding the reference noise signal to the clean heart signal. These two signals are then processed by the ANC algorithm designed under this effort, and described earlier. Following ANC processing, the recovered signal is recorded, displayed, and analyzed using a tape recorder, monitoring oscilloscope, and spectrum analyzer.

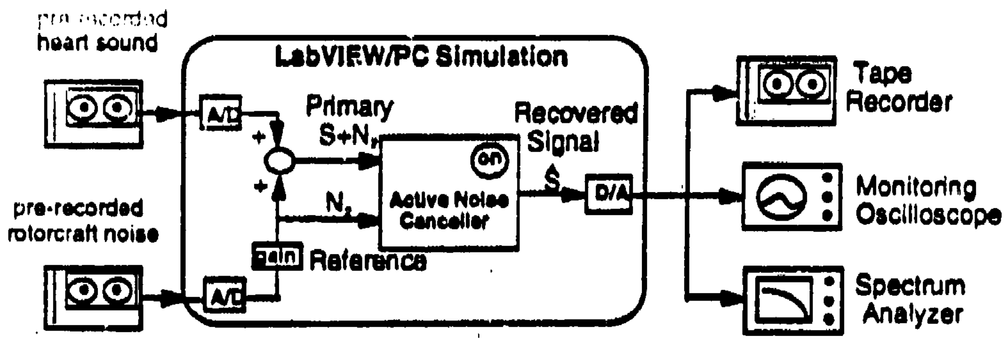


Figure 4.4-6: Engineering Simulation Setup

The engineering simulation provides an ideal environment for ANC algorithm development since we can adjust the noise both in intensity level and frequency characteristics, and repeatedly generate the same test condition. We can directly compare the recovered signal with the clean signal to identify possible distortions in the recovered signal. The engineering simulation, however, also has a disadvantage since it assumes an ideal but unrealistic noise environment where the noise component of the primary signal is identical to the reference noise. In addition, there is no "contamination" of the reference noise N_2 by the signal S, a situation we would expect to see in a real-world recording situation. In spite of these shortcomings, however, the engineering simulation provides us with a controllable development environment to evaluate a number of ANC processor design options.

Figures 4.4-7a and 4.4-7b show time histories of a clean heart signal and rotorcraft noise used for the engineering simulation (similar to those shown earlier in figures 4.1-1a and 4.1-2a). Figure 4.4-8a shows the primary channel signal, which is the summation of the clean heart sound and the rotorcraft noise. Figure 4.4-8b shows the recovered heart signal after ANC processing. From these figures, we can see that the ANC component indeed does an excellent job of noise cancellation and signal recovery. The conclusion is further verified by directly *listening* to the stethoscope signal . Without ANC, the heart sound is completely buried in the contaminated primary signal and is completely non-audible. With ANC processing, the heart sound becomes clearly audible.

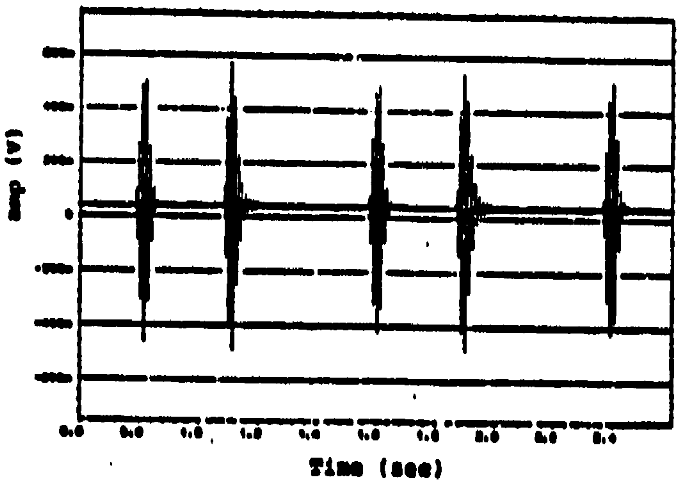


Figure 4.4-7a: Time History of Clean Heart Sound

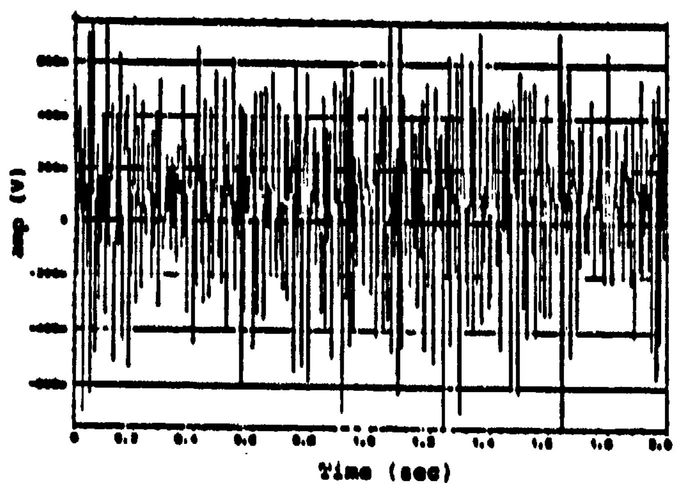


Figure 4.4-7b: Time History of Rotorcraft Noise

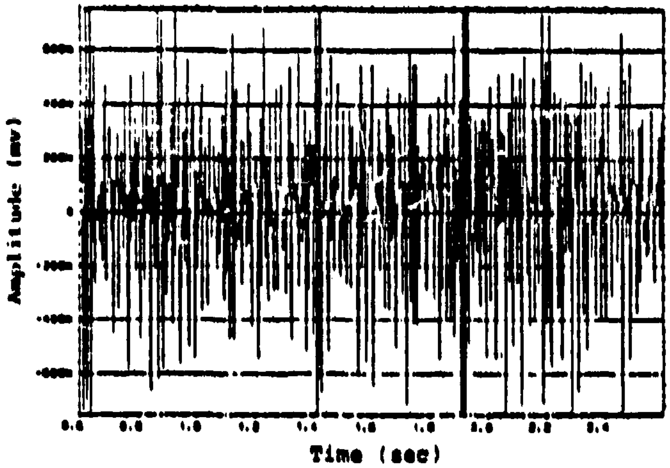


Figure 4.4-8a: Time History of Primary Channel Signal

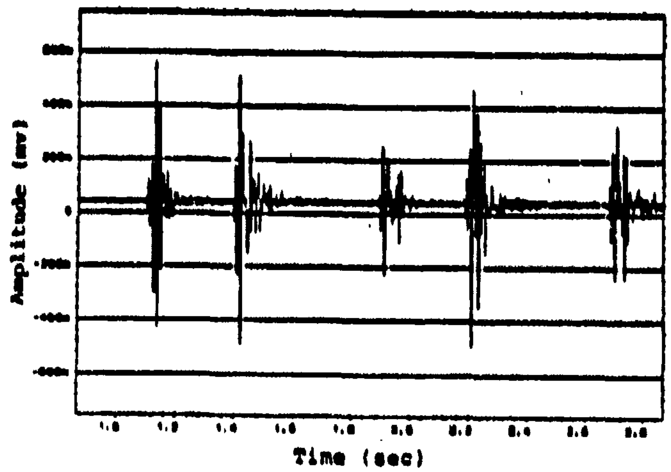


Figure 4.4-8b: Time History of Recovered Heart Signal

Figure 4.4-9 compares the three signal spectra: contaminated heart, recovered heart, and clean heart signals. We see that the ANC achieves a 10 to 15 dB noise reduction below 600 Hz while maintaining a close spectral resemblance between the recovered and clean heart signals, indicating minimal heart sound distortion.

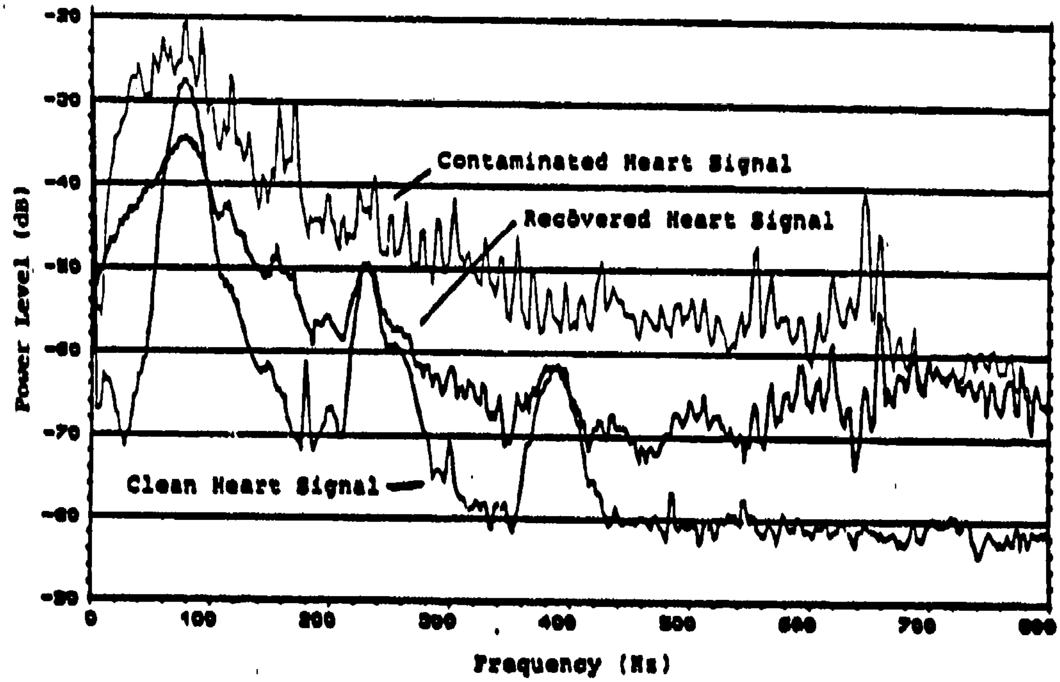


Figure 4.4-9: Comparison Between Clean, Contaminated, and Recovered Heart Sound Spectra

4.4.3 Dual Stethoscope Evaluation of ANC processing

A dual stethoscope evaluation was also conducted to evaluate the effectiveness of ANC processing on patient/transducer noise. Figure 4.4-10 illustrates the experimental set-up. Instead of using pre-recorded heart and noise signals, the primary and reference signals are obtained directly from a human subject in a simulated rotorcraft cabin environment (using pre-recorded amplified cabin noise). The primary and reference signals are then processed by the ANC processor, and the recovered signal is recorded, displayed, and analyzed on-line using the tape recorder, monitoring oscilloscope, and spectrum analyzer.

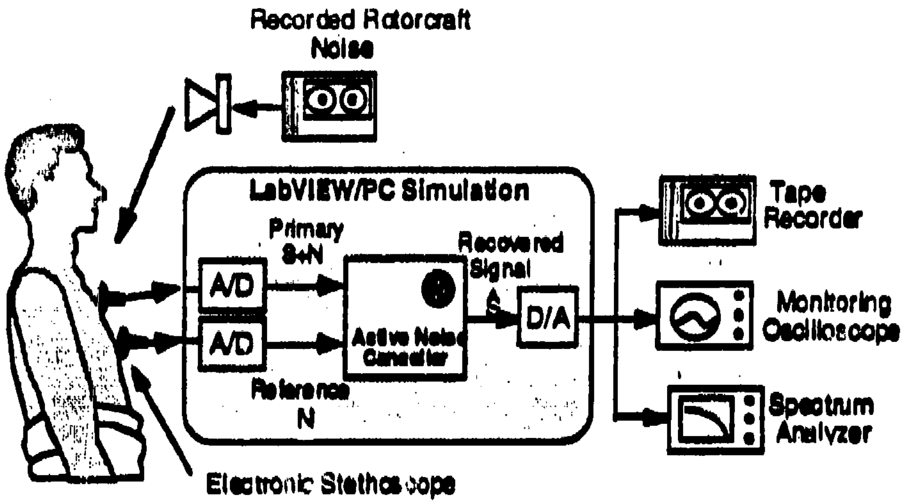


Figure 4.4-10: Dual Stethoscope Evaluation Setup

Figures 4.4-11a and 4.4-11b show the primary (contaminated) and recovered heart signals, respectively, using a finer time base resolution than shown earlier. From the figures, we can see that the ANC processor has obviously canceled the rotorcraft noise and recovered the heart sound signal from the contaminated primary channel signal. Note especially the ANC's capability for canceling rotorcraft noise spikes that look like heartbeats (e.g, at t=2.5 sec), a capability not achievable through classical filtering. Figure 4.4-12 compares the spectra of the contaminated and recovered heart sound signals, indicating a 10 to 15 dB noise reduction in the 50-350 Hz band. Listening directly to the corresponding contaminated and recovered heart sounds confirms this. The heart sound is auditorily buried in the noise (as it is visually in figure 4.4-11a) prior to ANC processing, while the recovered sound is very clear auditorily (again, as it is visually in figure 4.4-11b).

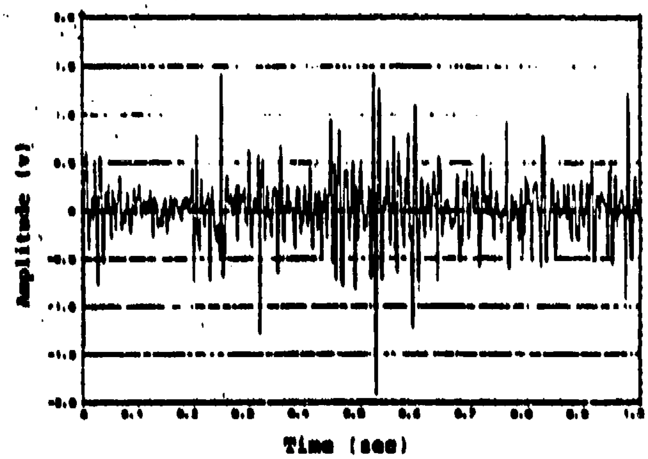


Figure 4.4-11a: Contaminated Heart Sound Signal

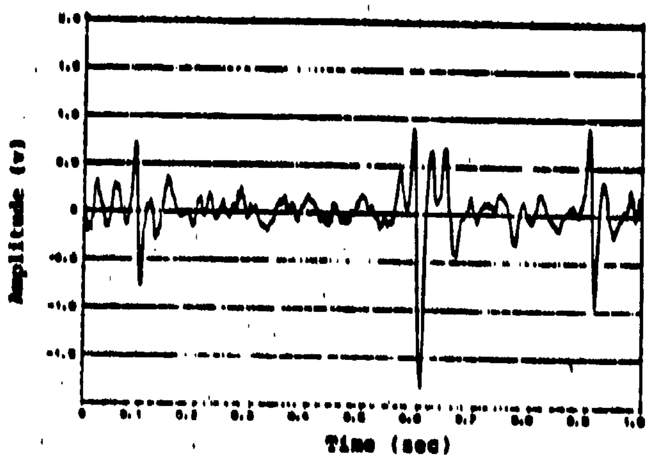


Figure 4.4-11b: Recovered Heart Sound Signal

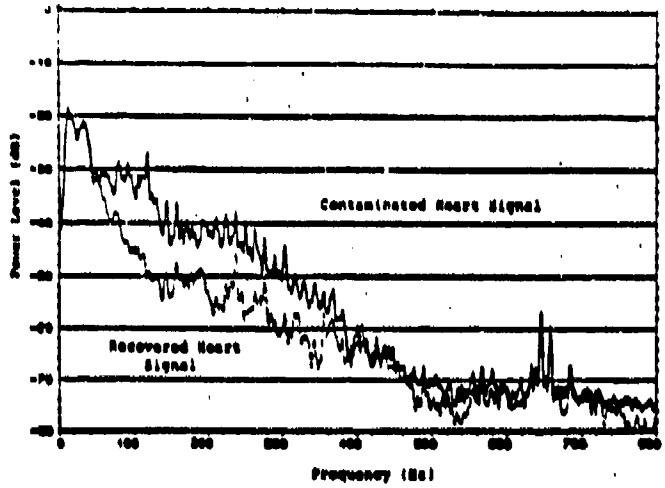


Figure 4.4-12: Comparison Between Contaminated and Recovered Heart Sound Spectra

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Effort

Our technical approach to demonstrating feasibility of a hybrid active/passive noise canceling stethoscope consisted of five tasks:

1. Characterization of medevac stethoscope problems
2. Evaluation of commercial components for ambient path noise cancellation
3. Demonstration of passive isolation for stethoscope path noise reduction
4. Development and demonstration of custom ANC design for stethoscope/patient path noise cancellation
5. Recommendation of development path for full-scope research prototype

We first characterized the medevac stethoscope problems and evaluated solution options. We began with a characterization of the signal and noise components. Teaching tapes for heart sounds and lung sounds were reviewed, spectrum-analyzed and modeled. In addition, we made several recordings in the laboratory and characterized the resulting sounds in the frequency domain. The noise environment was characterized by recording in the cabin of a commercial Bell Jet Ranger 206B helicopter. Spectral analysis of the recorded signals was performed to evaluate the noise characteristics at different flight conditions. We then established expected baseline performance with conventional stethoscopes, and with a selected electronic stethoscope. Psychoacoustic testing was conducted to evaluate the clarity of the transduced sounds in a simulated rotorcraft acoustic environment, and the results analyzed to define the detectability of the heart sound as a function of ambient noise level.

We next evaluated commercial components for ambient path noise cancellation, via review and evaluation of commercially available components. We reviewed several available headsets incorporating ANC techniques for use in the commercial aviation market, and selected the Bose Aviation Headset for further study. We also reviewed several available electronic stethoscopes, and selected the Labtron stethoscope for further study. We characterized the acoustic transfer functions (for both signal and noise). We evaluated the headset capabilities for active and passive noise reduction. We also evaluated the stethoscope's sensitivity to heart/lung sounds, as well as sensitivity to unwanted ambient sound transduction. Using a simulation of the rotorcraft environment, we demonstrated the capabilities of the combined headset and electronic stethoscope in canceling the ambient path noise at the medic's ears.

Following the ambient path cancellation demonstration, we demonstrated passive isolation for stethoscope path noise reduction, via a laboratory evaluation. This involved characterizing the stethoscope sensitivity to ambient noise as a function of passive acoustic shielding, and its placement.

We then developed and demonstrated a custom ANC design for stethoscope/patient path noise cancellation, to enhance the signal to noise ratio at the transducer. This effort began with the development of a PC-based ANC design, using the rapid-prototyping language LabVIEW. A non-real-time engineering simulation was then developed to simulate post-processing of the contaminated stethoscope signal. Pre-recorded heart signals were contaminated with pre-recorded rotorcraft signals, and then processed by the PC-based ANC algorithm. Results demonstrated effective recovery of the original stethoscope signal. Following this, we demonstrated ANC operation with a dual-transducer configuration, with a primary stethoscope at the heart and a second reference stethoscope at a remote location on the trunk of the body that senses N_2 stethoscope/patient path noises for cancellation with the noise in the primary stethoscope. Post-processing by the ANC design again showed significant reduction in signal contamination, and effective recovery of the signal.

Finally we recommended a development path for a full-scope research prototype, based on the results of the Phase I evaluation effort. The development path includes an enhanced performance version of the Phase I design, implementation as a single-board package for real-time recovery of the stethoscope signal in rotorcraft noise, and demonstration and performance evaluation both in the lab and in flight, with a broad-based user population.

5.2 Conclusions

The results of this Phase I effort demonstrate the feasibility of developing a hybrid active/passive noise canceling stethoscope for use in rotorcraft aeromedical evacuation. The major findings supporting this successful proof-of-concept demonstration can be summarized as follows.

An initial characterization of the problem was carried out to assess the impact of rotorcraft noise levels on conventional and electronic stethoscope sound clarity. A trained MD rated clarity as a function of noise level intensity, and it was found that ambient noise levels of 70-75 dBA or lower were required for unimpeded detection of heart sounds. Rotorcraft noise levels span the range from 80-90 dBA level for models with significant noise control treatment to 100-110 dBA levels for bare cabin interiors. Therefore, a stethoscope system designed for use in medevac rotorcraft, which typically have simple interior noise control treatments and noise levels in the 90-100 dBA range, will, on the basis of our psychoacoustic results, need to provide approximately 25-30 dB of effective reduction of the cabin noise, relative to the heart/lung sounds of interest.

The hybrid stethoscope system design evaluated in Phase I employed state-of-the-art passive noise control techniques and active noise cancellation (ANC) technology. The system consisted of an electronic stethoscope for sensing of heart/lung sounds, and an ANC headset to present the sounds to the medic for aural evaluation. For rotorcraft noise reaching the ear directly (N_1 noise), the commercially-available headset provided passive attenuation on the order of 10-20 dB above 200 Hz. Considered to be a high-quality design, the headset, made by the Bose Corp. for the general aviation market, provides additional active noise cancellation of 15-20 dB at low frequencies in the 40-300 Hz range, a range critical for listening to the generally low frequency heart/lung sounds.

Rotorcraft noise can also contaminate the transduction of heart/lung sounds by transmission into the body where it is picked up by the stethoscope, or by direct excitation of the stethoscope transducer (N_2 noise). The commercially-available electronic stethoscope used for the Phase I demonstration proved to be equally sensitive to acoustic noise acting on the case (the transducer *backside*), as on the diaphragm placed in contact with the body (the transducer *frontside*).

The Phase I study developed and demonstrated an ANC processor for stethoscope/patient path noise cancellation. A second stethoscope served as a noise reference, and was placed on the body at remote locations on the trunk where heart/lung sounds are diminished. An ANC processor was developed to process both signals, using the reference as a basis for adaptively estimating the noise in the primary, and then compensating the primary to recover a clear estimate of the uncontaminated heart/lung sound.

A non-real-time engineering simulation of the performance of the ANC algorithm yielded reductions of 10-15 dB below 600 Hz. A follow-on dual-transducer evaluation, using primary and reference stethoscopes on the body subjected to an ambient of rotorcraft noise, provided similar sound clarity enhancement, with noise reduced 10-15 dB below 350 Hz.

A quantitative assessment of relative noise contributions coming directly into the ear (N_1) and through the patient/stethoscope combination (N_2) showed both to be comparable in adversely affecting the listening process.

This Phase I effort has set the foundation for a follow-on program to develop an improved hybrid stethoscope system that combines both passive and active noise control techniques. A helmet meeting Army SPH-4B specifications would be used to provide 10-15 dB additional passive N_1 attenuation needed over the critical low frequency range. A modified electronic stethoscope transducer would be developed with reduced sensitivity to direct noise fields, using an enclosed bell cavity incorporating acoustic damping to minimize adverse effects of mechanical resonance's of the stethoscope on the body. Finally, the ANC processor would incorporate advanced ANC algorithms and tuned parameters to better match the noise/transducer characteristics, and will be hosted on a single-board microprocessor, for compact implementation and operational flexibility.

In summary, our Phase I results have clearly established the feasibility of the proposed hybrid stethoscope system. The Phase I study was specifically structured to be narrow in scope, but sufficiently detailed to set the foundations for a full functionality hybrid noise canceling stethoscope.

5.3 Recommendations

On the basis of these Phase I results, we recommend a Phase II effort focused on the development and demonstration of a prototype hybrid active/passive noise canceling stethoscope for rotorcraft aeromedical evacuation use. Table 5.3-1 highlights the basic differences between Phase I and Phase II, and shows how the results of the Phase I effort feed into the objectives of the Phase II programs.

For Phase I the basic objective of the program was to establish feasibility of the hybrid active/passive noise canceling stethoscope. The approach taken was to develop the overall architecture and demonstrate operation of the individual components. Under Phase II the objective will be to develop and evaluate a breadboard prototype of the system to evaluate real-time end-to-end operation. The technical approach will depend on an enhancement of the system architecture and the individual components, as well as extensive laboratory testing and field evaluation.

The acoustic environment considered under the Phase I effort was necessarily limited in scope. Primary consideration was given to patient heart sounds, and the focus was on a selected set of normal heart sounds. Under Phase II we propose to broaden the range of heart sounds for use in testing. In addition, we plan to incorporate lung sounds to further expand the test envelope of the proposed stethoscope. Under Phase I the rotorcraft noise was limited to synthetically generated white and narrow band noise (for early engineering testing), and selected pre-recorded segments of in-cabin noise recorded on a single Bell 206B helicopter. Under Phase II we propose to use an expanded array of pre-recorded rotorcraft sounds. Specifically we intend to obtain recordings from the two primary Army medevac rotorcraft, the UH-60 and UH-1, as well as popular civilian medevac rotorcraft, such as the Bell 206L and MBB BK-117.

Table 5.3-1: Features of Phase I and Phase II Efforts

Feature	Phase I	Phase II
Objective	Establish Feasibility of Design	Develop/Evaluate Breadboard Prototype
Approach	Develop Architecture & Demonstrate Operation	Enhance Architecture & Components Laboratory Testing & Field Evaluation
Acoustic Environment		
• Signal	Selected heart sounds	Broad range of heart/lung sounds
• Noise	Synthetic white & narrowband Civilian rotorcraft, prerecorded	Same as Phase I, plus range of military/civilian medevac rotorcraft
Stethoscope Transducers		
• Function	Primary and reference patient sounds	Primary and reference patient sounds Augmented with ambient reference
• Implementation	Commercially-available: Labtron	Custom design/fabrication • modified Labtron • closed-bell design (single, dual) • thin film transducer
• Testing	Acoustic measurements for signal sensitivity, noise rejection Laboratory environment	Same as Phase I, plus field testing
Headset/Helmet		
• Function	Patient sound amplification Ambient noise cancellation	Same as Phase I plus communications
• Implementation	Commercially-available ANC headset: Bose	Custom ANC helmet design/ fabrication • modified Bose • custom design for SPH-4B
• Testing	Acoustic measurements, for signal sensitivity, noise rejection Laboratory environment	Same as Phase I, plus field testing
ANC Processor		
• Function	Patient sound recovery from transducer	Same as Phase I, plus system housekeeping functions & user interface
• Implementation	PC-hosted SP LabVIEW S/W Platform LMS algorithm	PC-hosted with single-board DSP C-code implementation NLMS algorithm
Test and Evaluation		
• Protocol	Engineering measurements of components	Engineering and psychoacoustic evaluation
• Basis	Single-subject psychoacoustic tests Synthetic mixing of S&N Laboratory acoustic mixing	Multi-subject testing Same as Phase I, plus in-vehicle measurement

Under the Phase I study, two stethoscope transducers were used to generate primary and reference signals for the ANC processor. Under Phase II we intend to expand upon this dual transducer structure by augmenting the ambient noise measurements with a third reference microphone, located near or on the primary stethoscope. This will provide us with an additional degree of freedom in rejecting both patient and stethoscope noise signals, via an independent mixing parameter. Under Phase I, commercially/available stethoscopes were reviewed for their utility in the project, and a single transducer was selected: the Labtron electronic stethoscope. Under Phase II we intend to make significant improvements upon this transducer, via a custom design and fabrication effort aimed at improving signal pickup characteristics while rejecting the ambient noise acting on the transducer. Three alternative designs are contemplated for Phase II: a modified Labtron with significant *backside* shielding; a closed-bell design, using either single or dual acoustic chambers; and a thin-film transducer with inertial backing. Phase I testing of the stethoscope transducer focused on the acoustic characteristics, specifically signal sensitivity and noise rejection capabilities. All measurements were made in the laboratory environment, using either white noise test signals or rotorcraft noise recordings. Under Phase II we proposed to conduct the same type of measurements, but in addition intend to do extensive field testing in one or more rotorcraft.

The headset/helmet component of the stethoscope system evaluated under Phase I focused on the twin functions of patient sound amplification and ambient noise cancellation. Under Phase II the primary focus will be the same; however consideration will also be given to ensuring between-crew communications capabilities, to satisfy practical operating considerations. Under Phase I we were, by necessity, restricted to the use of commercially-available ANC headsets, developed for the general aviation (GA) market. After review, the Bose Aviation Headset was selected. Under Phase II, we intend to develop a custom ANC helmet prototype built around the SPH-4 U.S. Army rotorcraft helmet, which provides for enhanced noise and crash protection. The primary effort here will be to integrate a modified Bose headset within the design constraints of the SPH-4 helmet. We anticipate some custom design here. Testing of the headset/helmet component under Phase I was limited to standard acoustic measurements of signal amplification and noise rejection, conducted in the laboratory environment. Under Phase II we intend to conduct the same type of testing, but over a considerably expanded signal and noise test suite. In addition, we plan to conduct field testing to validate the basic laboratory results.

The function of the ANC processor under Phase I was limited to the recovery of patient sounds from the noisy transducer signal. Under Phase II this will again be the primary function of the ANC processor, but we intend to expand its capabilities to include system housekeeping functions and user interface functions, to support smooth operation of the overall stethoscope system. Under Phase I the processor was implemented on a general purpose PC configured for real-time analog I/O. Under Phase II we intend to upgrade this host with a digital signal processing (DSP) board, to ensure fast real-time end-to-end operation. This host, in turn will be transitioned to a single-board embedded system for the actual Phase II prototype. Under Phase I, the software development environment was the LabVIEW rapid prototyping signal processing environment. To ensure rapid real-time operation, Phase II will transition to a C-code implementation. Under Phase I, algorithm development was of necessity relatively limited, and focused on the conventional ANC design utilizing the standard Least Mean Squares (LMS) algorithm. Under Phase II we intend to transition to the normalized LMS (NLMS) algorithm and also intend to conduct engineering optimization studies to ensure high signal recovery performance and robust operation in the face of unmodeled disturbances.

The test and evaluation protocol used under Phase I focused primarily on engineering measurements of the individual components and made use of single-subject psychophysical testing of patient sound clarity. Under Phase II we intend to expand upon this test protocol, by incorporating more end-to-end testing of the complete prototype system. In addition we plan to make use of a larger subject population for psychoacoustic testing and statistical evaluation of sound clarity and noise rejection capabilities. Under Phase I, the primary testing made use of synthetic mixes of signal and noise, both electronically and acoustically in the laboratory. Under Phase II we plan the same test approach, but intend to considerably expand the combinations of the signal and noise across a range of vehicles and patient sounds. In addition, we plan extensive in-vehicle measurements for more realistic assessment of overall system performance.

Figure 5.3-1 schematically illustrates the difference between the Phase I design concept and the Phase II breadboard prototype. Under Phase I we have a dual stethoscope configuration providing us with primary and reference signals, driving a general purpose IBM PC-compatible. It runs a standard LMS ANC algorithm driving a commercially-available Bose ANC headset. Under Phase II, we propose a three measurement system, with significant redesign of the transducers to minimize sensitivity to ambient noise. An additional mixer component is shown (although it could readily be incorporated within the basic signal box), whose function is to weight the signal from the two reference transducers. The general purpose PC is replaced by a single board microprocessor-based system which generates the recovered signal for subsequent playback through a custom ANC helmet.

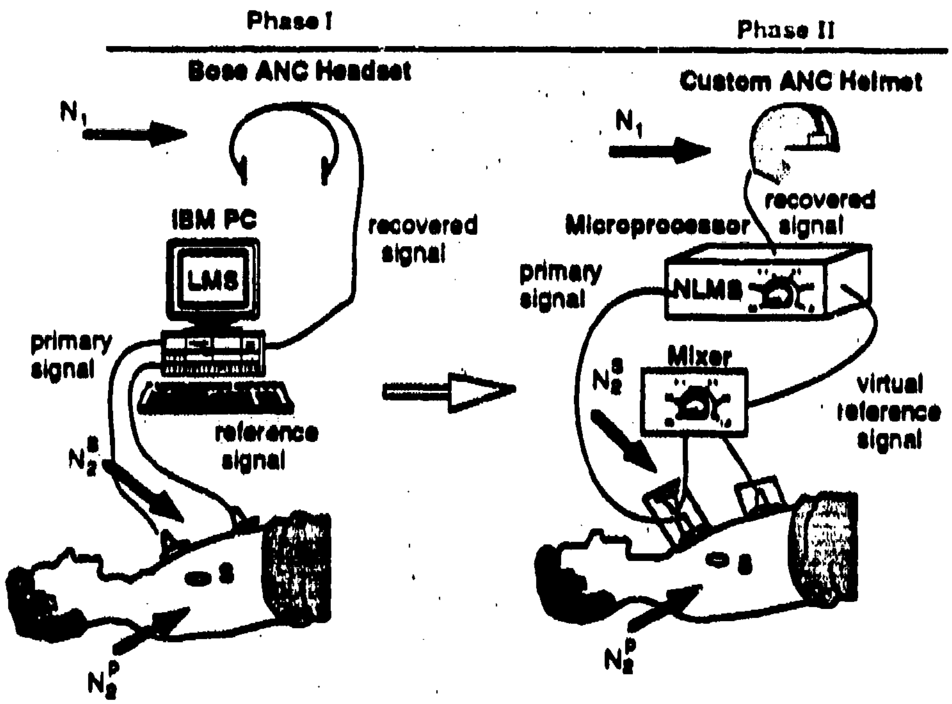


Figure 5.3-1: Phase I Design Concept vs. Phase II Prototype Configuration

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APPENDIX A: Equipment List for Experimental Validation

A test apparatus was built in the Sound and Vibration Laboratory at Tufts University for the simulation study of the proposed system. The simulation setup and the list of equipment used for the ANC studies, algorithm development, and evaluation are listed below:

- Power Amplifier, BGW 8000 TOROID Professional Power Amplifer
- Speaker System, Electro-Voice; Model 100S; Two-Way Constant-Directivity
- Electronic Stethoscope, Labtron 04-1060
- B&K Dual Channel Signal Analyzer Type 2032
- B&K Noise generator Type 1405
- Computer: Gateway 2000 486DX2/50E
- LabVIEW Software (version 2.5.2 January 1993)